Exploring Domain Knowledge and Personal Epistemology in the Development of Design Expertise in Novices

by

Christopher Donald Rennick

A thesis

presented to the University of Waterloo

in fulfilment of the

thesis requirement for the degree of

Doctor of Philosophy

in

Management Sciences

Waterloo, Ontario, Canada, 2025

Examining Committee Membership

The following served on the examining committee for this thesis.

External Examiner	Dr. Robin S. Adams Professor of Engineering Education Purdue University
Supervisor	Dr. Kenneth N. McKay Professor, Management Science and Engineering University of Waterloo
Internal Member	Dr. P. Robert Duimering Associate Professor, Management Science and Engineering University of Waterloo
Internal Member	Dr. Donna E. Ellis Adjunct Assistant Professor, Management Science and Engineering Director, Centre for Teaching Excellence University of Waterloo
Internal-external Member	Dr. Jonathan A. Fugelsang Professor, Psychology University of Waterloo

Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Engineering design problems are ill-structured, context-dependent, complex, dynamic, and domain specific; and as such, are heavily dependent on the knowledge and knowledge constructs of the designer. Prior research has identified the importance of personal attributes like knowledge, problem-solving strategies, meta-cognition, and personal epistemology as important to design problem solving, however few studies have investigated novice student knowledge and personal epistemology in detail, especially where these constructs interact with each other when designing.

This exploratory research investigated how undergraduate student knowledge and personal epistemological development manifest in design behaviours at two points in their first year: at the start of their first academic semester, and at the start of the second academic semester after having completed a university-level course on engineering design and potentially also a co-operative work term placement. These interviews investigated relevant experiences from the students' past, asked them to complete a concurrent think-aloud protocol while solving a design problem, and asked the students to reflect on their design process. The students' first-year design instructors were also interviewed at the end of the first academic semester to understand how design was taught to the student participants.

Case study methodology was selected to provide a detailed and rich description of each of the student participants' design experiences and behaviours. Deductive analyses were the primary methods used to understand student knowledge, quality of design process, and personal epistemology across the cases; however inductive analyses were also used to capture other related findings.

This thesis revealed connections between specific experiences/types of learning and student knowledge, personal epistemological development, and design behaviours. In tracking the students longitudinally through their first year, this thesis found that personal epistemology and knowledge developed in different ways, and at different times. The students were able to develop both the breadth, and depth of their knowledge, and demonstrated more informed design behaviours in the second interview, even though the majority of students did not develop their personal epistemologies.

The methods and techniques employed in this thesis to understand student knowledge and personal epistemology were novel approaches which show promise for future research. This thesis measured personal epistemological development in situ as students solved design problems; an approach which may be more efficient, and more accurate in measuring personal epistemology in the context of engineering design.

This thesis contributes to the role of knowledge structures in the learning of engineering design skills, how they differ between students, and how they change over time. These contributions can be leveraged to inform engineering design pedagogies and course structures, helping to establish useful baselines as well as development pathways for students with diverse levels of experience.

Acknowledgements

Preparing for and completing this work was a long journey that required extensive support from many people in both my personal and professional lives. Balancing full-time work, family, and this research has been exceptionally difficult, and I have almost certainly gotten the balance wrong at points over these many years, impacting those closest to me the most.

I would like to acknowledge all the help, conversations, and questions from my supervisor, Dr. Ken McKay. Thank you for taking a chance on another part-time PhD, especially when I didn't know what I wanted to study beyond "design education". Without your guidance over these many years, this thesis would not have been possible.

Thank you to my internal committee, Dr. Donna Ellis, Dr. Rob Duimering, and Dr. Jonathan Fugelsang. Your guidance at key moments was tremendously helpful and thank you for putting up with my long periods of radio silence between updates.

Thank you to Dr. Sanjeev Bedi. Without your pushing, I would not have started this process. You gave me the space and time I needed to work on this research and kept me motivated and moving forwards. Thank you also to the many, many others who have worked for or with the Ideas Clinic over these many years for your encouragement, and for accommodating my split attention as I worked on this research.

A big thank you to the students and instructors who participated in this research. Your early buy-in and continued interest in this research was invaluable as I began during the uncertainty of the Covid-19 pandemic. To the student participants, your openness and enthusiasm to take part in this research made this effort worthwhile. Thank you for taking time out of your evenings and weekends to talk with me; this research would not have been possible without you volunteering your time and energies.

Thank you to the many Waterloo staff and faculty, and the Canadian engineering education community who provided encouragement throughout my PhD; I truly appreciate your interest in my work.

Lastly, I want to thank my wife Sandra who has had to put up with lots of evening, weekend, and holiday writing sessions where I have been busy and distracted. Your love and support have been, and will continue to be, crucial to my successes. Thank you also to my friends and family, and especially my parents who have supported me throughout not just my PhD, but also all the many years that led up to this. One final thank you to Ferris, Beatrix, Naomi, and Lt. Worf for providing distractions when I needed them.

Table of Contents

Examining Committee Membership ii
Author's Declaration iii
Abstract iv
Acknowledgements vi
List of Figures xi
List of Tables xiv

1. Introduction 1
   1.1 Design and Designers 2
      1.1.1 Engineering Design Process 3
      1.1.2 Novice vs Expert Behaviour 4
      1.1.3 Problem-solving 7
      1.1.4 Problem Types 9
2 Design Cognition 12
   2.1 Role of knowledge in design and problem-solving 13
   2.2 Personal Epistemology 17
      2.2.1 Developing Student Epistemology in the Classroom 20
3 Teaching and Learning of Design in First Year 23
   3.1 Design Lectures and Short Duration Activities 24
   3.2 Design Projects 24
   3.3 Design Learning in Co-operative Work Term Settings 25
4 Research Plan 28
   4.1 Data Collection Methods 29
      4.1.1 Background Interview 31
      4.1.2 Verbal Protocol 32
      4.1.3 Retrospective Interview 32
      4.1.4 Instructor Interview 33
   4.2 Data Analysis Methods 33
      4.2.1 Knowledge Coding - Student Participants 35
      4.2.2 Design Process Coding 38
      4.2.3 Design Process Quality Coding 40
      4.2.4 Personal Epistemological Development Coding 43
      4.2.5 Knowledge and Epistemic Climate Coding - ME 100 Course Instructors 45
      4.2.6 Inductive Coding 46

4.2.7 Cross-Case Analysis Methods 47
4.3 Researcher Positionality 47
4.4 Overview of Thesis Structure 49
5 Results – Student Prior Knowledge 50
5.1 Student Participants 50
5.2 Preliminary Analysis of Participant Backgrounds 51
5.2.1 Chris 51
5.2.2 MJ 52
5.2.3 Oscar 54
5.2.4 Patrick 55
5.2.5 Michelle 56
5.3 Cross-Case Analysis 58
5.4 Summary of Findings 61
6 Results - 1A Design Process Analysis 62
6.1 Preliminary Analysis of 1A Design Process 62
6.1.1 Chris 64
6.1.2 Protocol Adjustment 67
6.1.3 MJ 67
6.1.4 Oscar 70
6.1.5 Patrick 72
6.1.6 Michelle 74
6.2 Cross-Case Analysis 77
6.2.1 Analysis of Design Timelines 77
6.2.2 Analysis of Informed Design Behaviours 80
6.2.3 Other Observations 81
6.3 Summary of Findings 83
6.3.1 Effects of Knowledge on Novice Designers' Design Behaviours 83
7 Results – Teaching and Learning in 1A Term 86
7.1 University Design Instruction – ME 100 86
7.1.1 Design Knowledge and Skills Instruction – DCAP 87
7.1.2 Design Knowledge and Skills Instruction – EGAD 88
7.1.3 Preliminary Analysis – Knowledge Instruction in ME 100 90
7.2 Preliminary Analysis of 1A Student Experiences 93
7.2.1 Chris 93
7.2.2 Michelle 96

7.2.3 Patrick ... 96
7.2.4 Oscar ... 97
7.2.5 MJ ... 99
7.3 Cross-Case Analysis ... 100
7.4 Summary of Findings ... 102
8 Results - 1B Design Process Analysis ... 105
8.1 Preliminary Analysis of 1B Design Process ... 105
8.1.1 Chris ... 107
8.1.2 Michelle ... 110
8.1.3 Patrick ... 113
8.1.4 Oscar ... 115
8.1.5 MJ ... 117
8.2 Cross-Case Analysis ... 120
8.2.1 Analysis of Design Timelines ... 120
8.2.2 Analysis of Informed Design Behaviours ... 122
8.2.3 Other Observations ... 124
8.3 Summary of Findings ... 126
8.3.1 Effects of Knowledge on Novice Designers' Design Behaviours ... 126
8.3.2 Impact of One Semester of Design Instruction on Novice Designers' Knowledge and Design Behaviours ... 127
9 Results – Personal Epistemological Development ... 129
9.1 Preliminary Analysis of Personal Epistemological Development – 1A ... 129
9.1.1 Chris ... 129
9.1.2 MJ ... 131
9.1.3 Oscar ... 132
9.1.4 Patrick ... 134
9.1.5 Michelle ... 136
9.1.6 Cross-Case Analysis ... 138
9.2 Conditions for Epistemological Development – First Year Design Course ... 141
9.2.1 Design, Communication and Professionalism ... 141
9.2.2 Engineering Graphics and Design ... 144
9.2.3 Preliminary Analysis of Epistemic Climate in ME 100 ... 145
9.3 Preliminary Analysis of Personal Epistemological Development – 1B ... 146
9.3.1 Michelle ... 146
9.3.2 Patrick ... 149

9.3.3 Chris ... 152
9.3.4 Oscar ... 154
9.3.5 MJ ... 158
9.3.6 Cross-Case Analysis ... 162
9.3.7 Other Observations ... 164
9.4 Summary of Findings ... 165
9.4.1 Effects of Personal Epistemology on Novice Designers' Design Behaviours ... 165
9.4.2 Impact of One Semester of Design Instruction on Novice Designers' Personal Epistemology and Design Behaviours ... 166
10 Discussion and Summary of Findings ... 168
10.1 Effects of Knowledge and Personal Epistemology on Novice Design Behaviours ... 169
10.2 Impact of One Academic Semester on Novice Design Behaviour ... 173
10.2.1 Other Observations ... 178
10.3 Interactions Between Knowledge and Personal Epistemology ... 179
10.3.1 Other Observations ... 183
11 Contributions, Limitations, and Future Directions ... 185
11.1 Contributions ... 185
11.1.1 Contributions to Development of Design Expertise in Novices ... 186
11.1.2 Methodological Contributions to the Study of Design Expertise ... 187
11.1.3 Implications for Design Education ... 189
11.2 Limitations ... 195
11.2.1 Methodological Limitations ... 196
11.2.2 Limitations of the Findings ... 197
11.2.3 Limitations of Analysis Methods ... 200
11.3 Suggestions for Future Research ... 201
11.4 Summary ... 203
References ... 204
Appendix A Interview Protocol – Student Participants ... 211
Appendix B Interview Protocol – Instructor Participants ... 217
Appendix C Detailed Data – Pre-university Experiences ... 219
Appendix D Detailed Data – 1A Design Activity ... 231
Appendix E Detailed Data – Student Experience Prior to 1B ... 256
Appendix F Detailed Data – 1B Design Activity ... 267
Appendix G Detailed Data – 1A Personal Epistemological Development ... 290
Appendix H Detailed Data – 1B Personal Epistemological Development ... 296

List of Figures

Figure 1 Visual representation of time spent in each stage of design process (Atman, 2019) 6
Figure 2 Sample student observation on ideal design process envelope (Atman, 2019)............................ 6
Figure 3 Cognitive process dimension (Anderson and Krathwohl, 2001).. 14
Figure 4 Two tier model of creative thinking (Runco & Chand, 1995) 15
Figure 5 Componential framework of creativity. Adapted from (Amabile, 1996)..................................... 16
Figure 6 The integrative model for personal epistemology development (simplified from Rule & Bendixen, 2010) 21
Figure 7 Timing of design courses, co-op work terms, and interviews in first year ME (student interview timing indicated with stars) 30
Figure 8 Map of thesis chapters to research questions.. 49
Figure 9 Design timeline of 1A interview with Chris.. 64
Figure 10 Overview of design process, 1A interview with Chris... 65
Figure 11 Overview of design process, 1A interview with MJ 68
Figure 12 Overview of design process, 1A interview with Oscar... 71
Figure 13 Overview of design process, 1A interview with Patrick... 73
Figure 14 Overview of design process, 1A interview with Michelle 75
Figure 15 Map of student performance against indicators of informed design behaviour, 1A interview . 81
Figure 16 Design timeline of 1B interview with Chris... 107
Figure 17 Overview of design process, 1B interview with Chris.. 109
Figure 18 Overview of design process, 1B interview with Michelle 111
Figure 19 Overview of design process, 1B interview with Patrick.. 113
Figure 20 Overview of design process, 1B interview with Oscar.. 116
Figure 21 Overview of design process, 1B interview with MJ 118
Figure 22 Map of student performance against indicators of informed design behaviour, 8-Stream students 1B interview 123
Figure 23 Map of student performance against indicators of informed design behaviour, 4-Stream students 1B interview 124
Figure 24 Overview of design process, 1A interview with Chris.. 130
Figure 25 Overview of design process, 1A interview with MJ 132
Figure 26 Overview of design process, 1A interview with Oscar... 134
Figure 27 Overview of design process, 1A interview with Patrick... 136

Figure 28 Overview of design process, 1A interview with Michelle 138
Figure 29 Indicators of informed design behaviours, sorted by level of personal epistemological development, 1A interview 140
Figure 30 Overview of design process, 1B interview with Michelle 149
Figure 31 Overview of design process, 1B interview with Patrick 152
Figure 32 Overview of design process, 1B interview with Chris 154
Figure 33 Overview of design process, 1B interview with Oscar 158
Figure 34 Overview of design process, 1B interview with MJ 161
Figure 35 Indicators of informed design behaviours, sorted by personal epistemology, 1B interview (stream in brackets) 164
Figure 36 Map of thesis chapters to research questions 168
Figure 37 Timing of design courses, co-op work terms, and interviews in first year ME (student interview timing indicated with stars) 173
Figure 38 Map of student performance against indicators of informed design behaviours, 1A and 1B interviews 175
Figure 39 Indicators of informed design behaviour in the 1A and 1B design activities, sorted by personal epistemology at time of interview 177
Figure 40 Overview of design process, 1A interview with MJ 184
Figure 41 Design timeline of 1A interview with MJ 231
Figure 42 Overview of design process, 1A interview with MJ 234
Figure 43 Design timeline of 1A interview with Jay 234
Figure 44 Overview of design process, 1A interview with Jay 236
Figure 45 Design timeline of 1A interview with Bond 238
Figure 46 Overview of design process, 1A interview with Bond 241
Figure 47 Design timeline of 1A interview with Oscar 243
Figure 48 Overview of design process, 1A interview with Oscar 246
Figure 49 Design timeline of 1A interview with Patrick 246
Figure 50 Overview of design process, 1A interview with Patrick 249
Figure 51 Design timeline of 1A interview with Jill 249
Figure 52 Overview of design process, 1A interview with Jill 251
Figure 53 Design timeline of 1A interview with Michelle 253
Figure 54 Overview of design process, 1A interview with Michelle 255

Figure 55 Design timeline of 1B interview with Michelle 267
Figure 56 Overview of design process, 1B interview with Michelle 271
Figure 57 Design timeline of 1B interview with Jill 272
Figure 58 Overview of design process, 1B interview with Jill 274
Figure 59 Design timeline of 1B interview with Patrick 276
Figure 60 Overview of design process, 1B interview with Patrick 280
Figure 61 Design timeline of 1B interview with Jay 280
Figure 62 Overview of design process, 1B interview with Jay 282
Figure 63 Design timeline of 1B interview with Oscar 284
Figure 64 Overview of design process, 1B interview with Oscar 286
Figure 65 Design timeline of 1B interview with MJ 286
Figure 66 Overview of design process, 1B interview with MJ 289
Figure 67 Overview of design process, 1A interview with Jay 291
Figure 68 Overview of design process, 1A interview with Bond 293
Figure 69 Overview of design process, 1A interview with Jill 295
Figure 70 Overview of design process, 1B interview with Jill 299
Figure 71 Overview of design process, 1B interview with Jay 301

List of Tables

Table 1 Summary of Perry's positions and stages 17
Table 2 King & Kitchener's (1994) Reflective Judgement Model 19
Table 3 Comparison of Perry's model and King & Kitchener's model (Felder & Brent, 2004) 19
Table 4 Mapping of interview sections to constructs under investigation 30
Table 5 Knowledge development from background experiences – Sample from Chris in 1A 36
Table 6 Codes used in design timeline construction (Atman and Bursic, 1998) 39
Table 7 Patterns of behaviour for different design strategies. Adapted from Crismond and Adams (2012) 41
Table 8 Student behaviours mapped to informed design strategies 42
Table 9 Summary of pertinent interview questions and their relationship to King and Kitchener's model 43
Table 10 Sample student quotes for each development stage 45
Table 11 Summary of student participants, 1A interviews (Fall 2021) 50
Table 12 Knowledge development from background experiences - Chris 52
Table 13 Knowledge development from background experiences - MJ 53
Table 14 Knowledge development from background experiences - Oscar 55
Table 15 Knowledge development from background experiences - Patrick 56
Table 16 Knowledge development from background experiences - Michelle 58
Table 17 Conceptually clustered matrix: Participant knowledge domains with relevance and level 60
Table 18 Design timelines, 1A interviews 63
Table 19 Percent of time spent in each design step during 1A interviews, Chris highlighted 66
Table 20 A summary of Chris' prior knowledge, adapted from Table 17 66
Table 21 Percent of time spent in each design step during 1A interviews, MJ highlighted 68
Table 22 A summary of MJ’s prior knowledge, adapted from Table 17 70
Table 23 Percent of time spent in each design step during 1A interviews, Oscar highlighted 71
Table 24 A summary of Bond’s prior knowledge, adapted from Table 17 72
Table 25 Percent of time spent in each design step during 1A interviews, Patrick highlighted 73
Table 26 A summary of Patrick’s prior knowledge, adapted from Table 17 74
Table 27 Percent of time spent in each design step during 1A interviews, Michelle highlighted 75
Table 28 A summary of Michelle’s prior knowledge, adapted from Table 17 76
Table 29 Design timeline(s) for student(s) with limited relevant knowledge 77

Table 30 Design timeline(s) for student(s) with relevant factual/conceptual knowledge and limited procedural knowledge 78
Table 31 Design timeline(s) for student(s) with relevant procedural knowledge 79
Table 32 Expected knowledge development from teaching activities in ME 100 91
Table 33 Summary of student participants, 1B interviews (Winter/Spring 2022) 93
Table 34 Updated knowledge development from experiences - Chris 95
Table 35 Updated knowledge development from experiences - Michelle 96
Table 36 Updated knowledge development from experiences - Patrick 97
Table 37 Updated knowledge development from experiences - Oscar 98
Table 38 Updated knowledge development from experiences – MJ 100
Table 39 Summary of knowledge taught in ME 100 102
Table 40 Summary of participant knowledge at time of 1B interview, 8-Stream indicated by 8-S, 4-Stream indicated by 4-S 104
Table 41 Design timelines, 1B interviews 106
Table 42 Percent of time spent in each design step during 1B interviews, Chris highlighted 109
Table 43 Percent of time spent in each design step during 1B interviews, Michelle highlighted 111
Table 44 Percent of time spent in each design step during 1B interviews, Patrick highlighted 114
Table 45 Percent of time spent in each design step during 1B interviews, Oscar highlighted 116
Table 46 Percent of time spent in each design step during 1B interviews, MJ highlighted 119
Table 47 Summary of changes in behaviour in 1B design activity, by participant 122
Table 48 Summary of personal epistemological development of each student participant, 1A 139
Table 49 Percent of time spent in each design step during 1A interviews, sorted by personal epistemological development 140
Table 50 Summary of personal epistemological development and indicators of informed design behaviour 162
Table 51 Percent of time spent in each design step during 1B interviews, sorted by personal epistemological development 163
Table 52 Summary of knowledge taught in ME 100 173
Table 53 Change in knowledge domains and levels between 1A and 1B interviews 174
Table 54 Summary of personal epistemological development for each student, 1A and 1B by knowledge level group 179

Table 55 Summary of students who demonstrated each informed design behaviour, 1A and 1B interviews 180
Table 56 Knowledge development from background experiences - Jay 222
Table 57 Knowledge development from background experiences - Bond 224
Table 58 Knowledge development from background experiences - Jill 228
Table 59 Percent of time spent in each design step during 1A interviews, Jay highlighted 237
Table 60 A summary of Jay’s prior knowledge, adapted from Table 17 238
Table 61 Percent of time spent in each design step during 1A interviews, Bond highlighted 241
Table 62 A summary of Bond’s prior knowledge, adapted from Table 17 242
Table 63 Percent of time spent in each design step during 1A interviews, Jill highlighted 252
Table 64 A summary of Jill’s prior knowledge, adapted from Table 17 252
Table 65 Updated knowledge development from experiences - Jill 259
Table 66 Updated knowledge development from experiences - Jay 263
Table 67 Percent of time spent in each design step during 1B interviews, Jill highlighted 275
Table 68 Percent of time spent in each design step during 1B interviews, Jay highlighted 283

1. Introduction

"Everyone designs who devises courses of action aimed at changing existing situations into preferred ones" - Herb Simon (1996)

Design is central to engineering practice, but what changes does one go through when a student starts to learn and study engineering design in first year? What kind of creativity is required – or possible – at the first-year level? How does a student learn the skills needed to solve design problems? Even more critically, what is meant by "engineering design"? Simon's quote above is a very broad definition of design that would encompass many tasks in one's day, including mundane tasks like how to fill an empty stomach. While there may be general design thinking skills and practices that transfer from domain to domain, there is evidence that there are important domain specific elements to design that can't be ignored (Vieira, et al., 2019). So, what is different about engineering design?

Within engineering, the many disciplines approach design in their respective fields differently. Domains where there are significant, well-recognised risks to human life (e.g., civil engineering, chemical engineering, aerospace engineering) often have strict best practices, codes, or standards that define the space within which design can take place – see Perry's Chemical Engineers' Handbook (Green & Southard, 2018), for example. Other fields have built up similar structures over time as the field has matured and engineers in those fields have had to repeatedly solve similar/related problems – see books like Code Complete in software engineering (McConnell, 2004), or the Art of Electronics in electrical engineering (Horowitz & Hill, 2015). Still others are quite young domains, where there is still much space for creativity and entrepreneurial thinking as the domain pushes on the frontier of scientific knowledge (e.g., nanotechnology engineering, biomedical engineering). However, to borrow from Simon's definition, what is true of design in all engineering domains is that engineering design is conducted by applying scientific principles to "devise courses of action aimed at changing existing situations into preferred ones", whether that science is computer science, physics, chemistry, or biology. Engineers Canada pushes that definition a little further by requiring that engineers be capable of designing solutions to complex, open-ended problems with appropriate attention to health and safety, the environment, cultural and societal considerations, and the law (Engineers Canada, 2016).

There have been several attempts to describe the knowledge base of engineering –Sheppard et al. (2009), for example describe 8 types of knowledge that are central to engineering practice. This thesis seeks to investigate the knowledge students bring with them as they start their undergraduate studies, the knowledge they develop in their first term(s) of their engineering program, and how they leverage this to solve engineering design problems. Similarly important to how students develop and use their knowledge is how they view what knowledge is – that is, their personal epistemology. This thesis also seeks to understand how first-year engineering students develop their personal epistemology as they take part in teaching and learning experiences, co-operative work terms, and other related activities. Lastly, through detailed case studies of multiple students, this thesis seeks to identify patterns of how knowledge and personal epistemological development are reflected in design process quality. This thesis has broad implications on teaching practices for novice engineering students, outcomes and supports required for novice engineering students on co-operative work terms, and the types of pre-university training which best prepare students to solve ill-structured engineering design problems.

Chapter 1 of this thesis will describe current research on design and designers, design processes, expertise in design, as well as research on problem-solving and types of problems. Chapter 2 provides an overview of design cognition and the role of knowledge and personal epistemological development on design. Chapter 3 describes design teaching and learning in first year in both the university environment as well as in the co-operative work term environment. Chapter 4 describes the research plan, data collection, and analysis methods used in this thesis. Chapter 5-8 describe the results of the investigation into student knowledge and its impacts on design process. Chapter 5 provides a description of pre-university experience for the participants. Chapter 6 discusses how the knowledge from this pre-university experience is utilized when solving a design problem. Chapter 7 describes the teaching and learning activities students received in their first academic semester as well as an overview of any other relevant experiences, including from their first work term (where applicable), and Chapter 8 discusses how the participants used their knowledge when solving a new design problem in their second semester. Chapter 9 discusses the personal epistemological development of the participants in their first academic semester and how that is reflected in their design process, the epistemic climate of the first year design course and how that may have contributed to the development of student personal epistemology, and ends with a discussion of the resulting epistemological development of the participants and how that is reflected in their design process at the start of their second academic semester. The remaining chapters are discussion, contributions, and conclusion.

1.1 Design and Designers

Design problems are clearly not all created equal. There have been many attempts at creating typologies of design and design problems, one such model is given by Pahl et al. (1984):

- **Original design**: involves elaborating an original solution principle for a system with the same, a similar, or a new task.

- **Adaptive design**: involves adapting a known system (the solution principle remaining the same) to a changed task. Here original designs of parts or assemblies are often called for.
- **Variant design**: involves varying the size and/or arrangement of certain aspects of the chosen system, the function and solution principle remaining unchanged. No new problems arise because of changes in materials, constraints, technological factors, etc.

Following up on these three types, Pahl et al. describe a survey where they had found that 55% of products in the mechanical engineering industry represented adaptive design, with only 25% being original design. While it is simplistic to think that as a device grows in complexity (like a modern automobile, for example), that it is entirely an original, adaptive, or variant design (as opposed to some combination of all three); it may be that the design tasks of individual designers within that complex device fit neatly on this scale (Howard et al, 2008).

Pahl's thinking is in line with Dorst (Dorst, 2011) who described two types of abductive reasoning that are prevalent when designing: the more common "Abductive-1" – where a designer applies known working principles to design an object/service/system that is capable of achieving an understood "desired value" – and the more open and ill-structured "Abductive-2" reasoning – where the designer knows only the desired value of the situation, but doesn't know either the working principle or the object to achieve that desired value. It would seem then, that improving designers' skills at conducting adaptive design, or the corresponding abductive-1 reasoning, would potentially have a large impact on the engineering design field. But how would you go about improving these skills? What skills are actually in use when designing?

The study of design and designers has taken many approaches to i) understanding design, and ii) understanding what makes some designers "better" or more successful than others. In general, this past research has employed methods at two primary levels: the behavioural (what do designers *do* when they are designing), and cognitive (what are designers *thinking* while they are designing) – which includes the neuro-cognitive (what are designers' brains doing when they are designing). Before describing the cognition and behaviour of designers, it is useful to describe the steps required to design.

1.1.1 Engineering Design Process

While there are seemingly infinite ways to describe the steps that a designer must go through when designing – often referred to as the steps of the design cycle, so named to capture the inherent iteration involved when designing – the eight steps as described by Atman (Atman, 2019) can provide a foundational model to work from. Atman synthesized these steps by conducting a content analysis of multiple engineering textbooks and has used the subsequent model to study designer cognition and behaviour for more than 25 years. While this model does not capture the steps involved in implementing a design into a tangible product (as that is not the focus of Atman's work), it appears to describe the initial development of a design concept at the level required for exploring the cognitive processes associated with design. Atman's model consists of eight activities, grouped in three stages:

Problem scoping:

1. Problem Definition – define the problem
2. Gather Information – search for and collect information

Generate alternative solutions:

3. Generate Ideas – think up potential solutions
4. Model – detail how to build solution(s) to the problem
5. Feasibility analysis – assess workability of possible solutions
6. Evaluation – compare and contrast possible solutions

Project realization:

7. Decision – select idea or solution among alternatives
8. Communication – communicate the design to others

While other models, like the engineering design process described by the Massachusetts Department of Education are slightly different – see Massachusetts Department of Elementary and Secondary Education's design curriculum (2020), or its application in the Engineering Design Self Efficacy Instrument (Carberry, et al., 2010) – they can be reasonably mapped to each other (the Massachusetts DoE use "construct a prototype", which is one way of conducting feasibility analysis, for example).

1.1.2 Novice vs Expert Behaviour

Numerous studies have examined the differences in behavior between novice and expert designers. One of the most influential in this field is Atman, who conducted multiple verbal protocol analysis studies with engineering students (first and fourth year) and with experts (domain-specific experts, and engineering experts) over several decades. During this time, 177 individuals participated in a series of controlled, lab-based design tasks using a concurrent think-aloud protocol as they designed. The transcripts were then coded based on the steps of the design process outlined above. From these studies, Atman (2019) found that when comparing experts to first year students, experts:

- Spend more time solving the problem
- Delay modelling until later in the design process, spending more time in problem scoping
- Gather more information, and that information covers a broader set of issues

- Consider a larger, and more broad, set of objects in their solution; transition more frequently across objects and categories of objects; and narrow their focus to a few that they then spend more time on

Similar findings have been reported in the problem-solving literature as well; Pretz, Naples and Sternberg (2003) summarized these findings as follows: experts spent more time finding a useful problem representation than novices, and once found, were able to move through the solution much faster than novices did. In addition, they noted that expert problem-solvers seemed better able to see the underlying structure of a problem which aids them in identifying and activating useful prior knowledge; a finding observed by others as well (Jonassen, 2011).

Mullins et al. (1999) found that students who had completed the first semester of an engineering undergraduate program spent more time solving problems, transitioned more between design activities, and considered more design criteria; however, the quality of their solutions did not improve. Atman et al. (Atman, et al., 2005) in a study comparing first and fourth year engineering students found that fourth year students spent more time solving the problem, more time on project realization, transitioned more (and more frequently) between design activities, covered a broader set of issues in their information gathering, and created higher quality products. First year students in this study spent more time on problem definition than on any other activity and spent virtually no time on project realization.

Atman frequently presents participants' design processes as timelines to illustrate the difference in design behaviour between designers with varying levels of expertise. Figure 1 shows the timelines for three first-year students and three graduating seniors who produced a low quality, middle quality, and high-quality design artifact, respectively (Atman, 2019). These diagrams show the rapid movement between the design stages for processes which generated high-quality designs, as well as the longer engagement times. For experts, Atman describes the shape of the timeline as a "cascade", and when teaching design process to undergraduate students using timelines, Atman has shown the drawing in Figure 2 (which was originally done by a student) as a visual way of displaying this cascade design process.

Cross (2018), in summarizing the nature of design expertise, stated three main ways in which expert designers think and behave differently from novices. Firstly, expert designers seem to "frame" design problems early in the process. The process of "problem setting" – of which framing is a part – described by Schon (1983) represents the cognitive work of imposing some structure on an ill-structured design problem. During this process, a designer will set boundaries on the problem and will decide which parts of the problem to pay attention to. In Schon's words (pg. 40): "Problem setting is a process in which, interactively, we *name* the things to which we will attend and *frame* the context in which we will attend to them."

Experts appear to perform this problem framing early in the process but will also re-evaluate their frame throughout the design process (Cross, 2018).

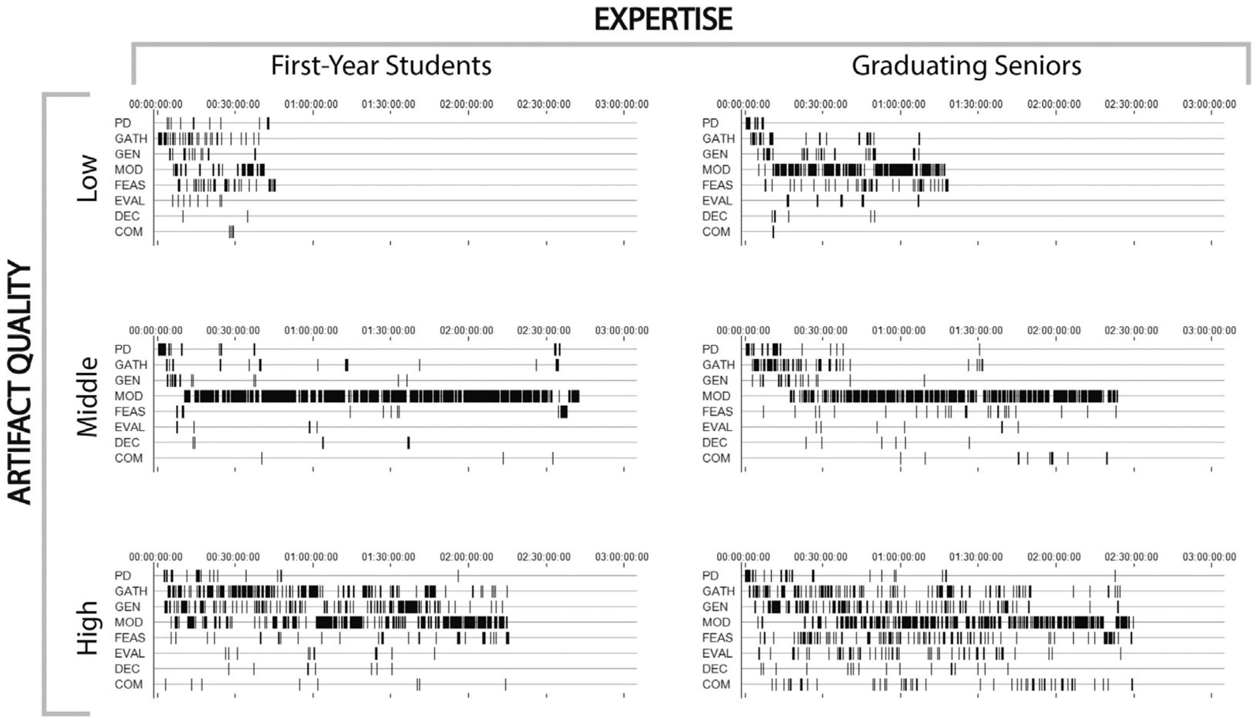


Figure 1 Visual representation of time spent in each stage of design process (Atman, 2019)

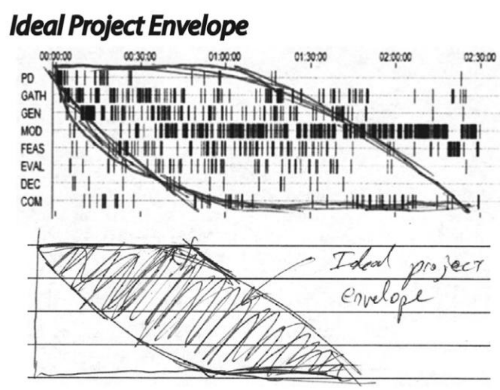


Figure 2 Sample student observation on ideal design process envelope (Atman, 2019)

The second behaviour that Cross observed in expert designers is rapid solution conjecturing. Experts demonstrated a solution-focused design process where the solution conjecture was used to refine their understanding of the problem. For an expert, the constraints on a problem situation are derived from three sources: the problem itself, past experience, and from learning derived from exploring possible solutions.

The third behaviour of expert designers has been described as the “co-evolution of problem and solution”. Since design problems are rarely fully specified at the onset, expert designers will adjust both the problem and solution space until a useful match is achieved: "creative design involves a period of exploration in which problem and solution spaces are evolving and are unstable until (temporarily) fixed by an emergent bridge which identifies a problem-solution pairing" (Dorst & Cross, 2001). While this is a different way of describing the process of designing, it is consistent with the findings of Atman: expert designers will transition from early steps in the design process (problem scoping) to later steps (generating solutions and project realization) and vice versa more frequently than novices.

There are important differences between the work of Dorst and Cross, and that of Atman which are worth mentioning. Atman presented the problem of designing a playground, and while there are a very large number of ways of assembling playground components into a complete structure, this problem more closely resembles a *variant* design as described by Pahl (Pahl, et al., 1984). The study by Dorst and Cross (2001) on the other hand, was seeking to investigate design creativity, and so the problem was more of the *adaptive*, or possibly *original* type (Dorst and Cross presented user data on the types of litter generated while riding a train as well as user comments on the current disposal solution and tasked designers to improve the situation). The problem presented by Dorst and Cross is more open-ended and ill-structured, with more space for creativity. Another significant difference between the studies was the participant pool. Dorst and Cross were studying industrial designers, while Atman was investigating engineering designers and engineering students.

Cross (2011) also observed that expert designers will sometimes treat a well-defined problem statement as an ill-defined one, intentionally making the problem more difficult to solve. This observation builds on the work of Thomas and Caroll (1979) who defined designing as a type of problem-solving where the designer views the problem as being ill-structured. Cross calls these designers "ill-behaved problem-solvers", pointing out that their behaviour is contrary to more traditional expert problem-solvers who look for the easiest way possible to solve a given problem. This is again consistent with the findings from Atman: experts consider a broader range of objects when developing their solution compared to novices. By broadening the scope of the problem, they are making the problem more difficult to solve. Novices, with their more limited domain and design expertise, seem to attend only to the issues that are given in the problem statement.

1.1.3 Problem-solving

In the design literature, there is consensus that designing is not problem-solving; designing is generally considered to be something *more* than problem-solving. There are, however, still things to be learned from the literature on problem-solving. Lawson and Dorst (2009) present "design as problem-solving" as one of three models for understanding design (design as learning, and design as evolution being the other two). They characterise problem-solving as the act of posing a problem, searching for a solution, evaluating alternatives, and selecting a solution; and certainly, these steps are present in designing. Comparing this model to the one used by Atman, for example, covers most of the 8 steps with significant reductions in the problem scoping phase, and an abbreviated communication step (as clients are rarely involved in more traditional problem-solving). Understanding expertise in problem-solving then, could be useful in describing the cognitive work of designing. Cross (1990) further reinforces this view: expert designers will frequently approach designing by posing solution conjectures. These possible solutions may help refine the designer's understanding of the problem, may illuminate criteria or constraints, or places where there are contradictions requiring future compromise. The behaviour of these design experts could be perceived as a series of problem-solving processes with each of their solution conjectures until they achieve an acceptable result. In a sense, engineering design can be viewed within the problem-solving realm but being something more than *general* problem-solving; it has specific characteristics not found in general problem-solving.

If problem-solving and designing can be viewed as a skill, or perhaps a series of skills, the cognitive science literature has much to offer in describing how such skills are acquired, and how experts differ from novices. Ericsson (2003) describes traditional theories of skill acquisition as including an initial cognitive phase where the underlying knowledge of the domain is acquired, followed by a second associative phase. During this second phase, learners have achieved a functional level of performance based on learning from failure, or from feedback of other kinds. After operating at this phase for a period of weeks, or maybe months, learners enter the third phase where that skill can be done with little conscious effort: the autonomous phase, which Kahneman referred to as System 1 thinking (Kahneman, 2011). While this process describes the learning associated with relatively simple tasks at a moderate level of performance, recognized experts in a domain have expanded their skill(s) beyond this point. Acquiring expert performance requires an ability to self-monitor, recognize deficiencies, seek out new challenges or learning opportunities – a process Ericsson has called "deliberate practice" – all while building experience in the domain. Expert-level thinking, then, has a significant meta-cognitive component. Mosier et al. (2018) in summarizing the metacognitive differences of experts, describe how an accomplished expert (a surgeon in their case) can transition between automatic thinking, and a slower, more deliberate thinking process (Kahneman's System 2 thinking) when they perceive something unusual about the situation at hand. Mosier et al. go on to add that experts have sophisticated mental models of their domain, an ability to recognize "typical" situations, and a library of decision-making routines, much of which is "tacit knowledge" of the domain. Tacit knowledge represents knowledge that is generally deployed automatically and is difficult to verbalize or explain to others. It is sometimes described as "know-how" (Frise, et al., 2003), and might best be learned by deliberate performance (i.e. through in situ experience of the domain) as opposed to through deliberate practice, which seeks to isolate specific skills once they have been identified as important to expert-level performance.

Regardless of the differing views on design and problem-solving, a simple observation is that designers are solving a problem, and that problem-solvers often design solutions. In fact, the cognitive science literature generally views 'design' within the problem-solving realm of discussion if it is discussed explicitly at all. Beyond the core cognitive processes related to problem-solving, there are differences when solving design problems, and these are discussed further in the next sub-section.

1.1.4 Problem Types

What makes engineering design problems different from general problems? What seems to make most design problems difficult to solve? Namely, what distinguishes them from other types of problems that people may be required to solve? Jonassen (2000) in his typology of problems provides one lens to examine the structural differences between design problems and other types of problems. According to Jonassen (2011), there are five external characteristics of problems:

1. Structuredness
2. Context
3. Complexity
4. Dynamicity, and
5. Domain specificity

Well-structured problems have little or no missing information, the problem description provides all the information needed to solve the problem; they often have a single correct answer with a prescribed solution process. At the other end of the continuum, *Ill-structured problems* are often multi-disciplinary in nature, have missing or conflicting information, have many acceptable paths to the solution with many (or perhaps no) acceptable solutions. Ill-structured problems may also possess multiple success criteria and so typically require the solver to apply their judgement to shape the problem and solution spaces.

Related to structuredness is the context of the problem. Typically, in a well-defined problem the context that the problem is situated in has little impact on the solution – or put another way, a well-defined problem is often represented in the abstract, devoid of any context. The context is often presented as a surface detail of the problem, which is unimportant to finding a solution to the problem. For example, in a typical physics problem of simulating projectile motion, the problem could be describing a rocket, a ski jumper, or a golf ball, but regardless of the situation in the story, the solver still applies the same formulas in the same, predictable ways. This is contrasted to ill-structured problems where the context can be central to the problem itself, and removing the context of the problem can remove all meaning.

According to Jonassen, design problems are ill-structured, and highly context dependent. While a problem can be ill-structured due to other factors, the problem's context can contribute significantly to the presence or lack of structure. For example, think about the problem of a craftsperson needing to hold on to their work piece safely. A problem statement for this could be to design a device that clamps an object to a table. This problem as stated – with no context given – is basically unsolvable. Most people would immediately want to know more about this situation: what are they clamping? Is it round or rectangular? How big is it? How much access does the craftsperson need to the object to work on it? Is the object hard or soft? Clearly this problem is also highly ill-structured; there are innumerable solutions to this problem – searching a popular online marketplace for "clamp" reveals over 100,000 products.

Complexity is defined by Jonassen as i) the breadth of knowledge required to solve the problem, ii) the intricacy of solution procedures, iii) the interrelationships between problem elements, iv) the number of unknowns in the problem space, and v) the interdisciplinarity, dynamicity, and legitimacy of alternative solutions. There is significant overlap between structuredness and complexity – with ill-structured problems tending to be more complex – however, complex and well-structured problems (e.g., chess), and ill-structured problems with little complexity also exist (e.g., what to eat for lunch).

Dynamicity of a problem refers to the degree to which problem elements change over time. Software development can be a highly dynamic problem domain as the problem – and problem criteria – changes as the problem is solved. Highly dynamic problems are very difficult to solve (evidenced by the many software projects that overrun on time and/or costs, see Glass (1997) for one discussion on the subject). Ill-structured problems can be expected to have more dynamicity than well-structured problems. This is especially true for design problems as they are often solving problems for people, and people's needs shift over time and as they learn more about the problem.

Finally, domain specificity refers to the degree to which the problem is situated in a single domain. Problems with high domain specificity may require solution procedures that are unique to that domain or may limit the usefulness of more general problem-solving strategies. In engineering design, which is highly domain specific, there is often a "know-how" (Frise, et al., 2003) component to finding solutions to problems. Know-how can be thought of as procedural knowledge (knowledge of "how" to do something), as opposed to declarative knowledge (knowledge of "what" something is). In some disciplines within engineering, this know-how has well-understood structure and is taught alongside the more theoretical concepts in the domain (e.g., books on software engineering best practices, see McConnell, 2004).

To summarize, real-world design problems are typically ill-structured, complex, and dynamic; and for engineering problems, they are also highly context dependent, and domain specific. Applying these factors to the types of design problems outlined by Pahl, original designs would tend to be more ill-structured, more dynamic, and may be more complex (due to them frequently requiring multi-disciplinary solutions) as compared to adaptive designs. Likewise, adaptive designs would tend to be more ill-structured and complex than variant designs. This combination of factors makes for problems that are more difficult for people to solve as it puts significant load on cognitive resources. The potential implication arising from these observations for training novice designers is the more complex, and more ill-structured a design problem is, the more support that students will need to solve it; at least until they have built up the cognitive resources to solve it on their own. Now that we have examined the nature of design problems, the next chapter will discuss the important elements of the *designer*.

2 Design Cognition

In addition to describing differences in problem variations and representations, Jonassen (2000) describes the "individual differences" that a problem-solver brings to bear on a problem. These include knowledge – domain-specific knowledge, structural knowledge (how different knowledge domains integrate together), procedural knowledge (know-how), and conceptual knowledge – as well as other cognitive skills/traits like general problem-solving strategies, cognitive controls (like metacognition, and reflection-in-action (Schon, 1983)), self-confidence, motivation, and personal epistemology. Looking specifically at designing, Crismond and Adams (2012) in a meta-literature review of design literature identified seven key performance dimensions that are central to informed design practice:

1. Learning while designing
2. Making and explaining knowledge-driven decisions
3. Working creatively to generate design insights and solutions
4. Perceiving and taking perspectives intelligently
5. Conducting sustained technological investigations
6. Using design strategies effectively
7. Integrating and reflecting on knowledge and skills

In comparing this list with the individual differences described by Jonassen, there is alignment with six of the points:

- **Learning** while designing is one element of cognitive controls – as part of Schon's reflection-in-action, experienced designers are able to listen to the "back-talk" of design situations and adjust their strategies based on incremental decisions while designing (Schon, 1983) (Adams, et al., 2003).
- **Making and explaining** knowledge-driven decisions requires both declarative and domain knowledge and the ability to justify decisions (which relates to personal epistemology, to be explained more below).
- **Perceiving and taking perspectives intelligently** describes a designer's ability to empathize with users, see the big picture of the design task, and identify priorities. While this is not described by Jonassen as such, it certainly relies on both procedural and structural knowledge of a domain and would benefit from advanced personal epistemology and reflection-in-action.
- **Conducting sustained technological investigations** requires knowledge at all levels described by Jonassen: declarative knowledge of the domain, procedural knowledge as it relates to the tools and methods of the domain, and structural knowledge to integrate the different knowledge bases of the domain.
- **Using design strategies effectively** hinges on a designer's procedural knowledge of how to conduct design.
- **Integrating and reflecting on knowledge and skills** requires structural knowledge of the domain, and meta-cognition to reflect on design progress.

One element not captured by Jonassen is **creativity**. This is not totally surprising in that creativity is rarely required (or indeed, even valued) in well-structured problems, and as Jonassen was describing a complete range of problem types from well- to ill-structured, creativity would play a very small role in many of the problem types he described. However, creativity is crucial in virtually every stage of design (Howard, et al., 2008) (Rennick & McKay, 2018). Howard et al. put it quite succinctly: "Creativity is an integral and essential part of the engineering design process. Without creativity in design there is no potential for innovation, which is where creative ideas are actually implemented and transformed into commercial value"; though they don't believe that traditional models of design (especially the linear ones used to teach novices) represent creative processes well. In their view, the divergent-convergent models of design (like the double diamond process) align better with contemporary understandings of creative processes. Connecting back to Pahl et al.'s (1984) categories of design outputs (viz. original, adaptive, variant, and routine designs), Howard et al. reframe these categories by examining where in the design process the designer is being creative:

- a designer producing an original design is creative in the concept of their solution
- a designer producing an adaptive design is creative in their analysis of the problem/task
- a designer producing a variant design is creative in their implementation of their solution

It is only in routine problems where creativity may not be present; though Howard et al. do propose that a designer may choose to pursue an original output instead of a variant design output (for example), which may alter their subsequent process. To consciously select the intended category of design output, however, the designer would certainly need a deep understanding of the field of potential solutions and related problem frames to ensure they are producing a novel solution.

The roles of different knowledge structures, cognitive controls, and personal epistemology on problem-solving and designing will be examined next.

2.1 Role of knowledge in design and problem-solving

Knowledge plays a significant role in design. Jonassen includes four different forms of knowledge in his design theory of problem-solving, and Crismond and Adams (2012) include the words learning, knowledge, or intelligent in four out of seven of their performance dimensions. While the language sometimes differs, Jonassen (2000) in general is aligned with Anderson and Krathwohl's (2001) summary of the "Knowledge Dimension" which includes:

1. Factual Knowledge – the basic elements students must know to be acquainted with a discipline or solve problems in it.
2. Conceptual Knowledge – the interrelationships among the basic elements within a larger structure that enable them to function together.
3. Procedural Knowledge – How to do something, methods of inquiry, and criteria for using skills, algorithms, techniques, and methods.

4. Metacognitive knowledge -Knowledge of cognition in general as well as awareness and knowledge of one's own cognition.

From this point onwards, factual and conceptual knowledge will be used instead of the more generic declarative knowledge. Sheppard et al. (2009) describe the types of knowledge used in engineering differently. In their summary, they include eight types of knowledge: theoretical tools (math-based and conceptual, engineering science knowledge), fundamental design concepts (operational principles and normal configurations), criteria and specifications relevant to a specific engineering field (e.g. pressure vessel standards), quantitative data (physical properties in formulas), practical considerations (tacit knowledge, rules of thumb, heuristics), process-facilitating strategies (project management, leadership, teamwork, communication, etc.), and contextual and normative knowledge (knowledge of values, norms, contexts). Not all of these apply to design, though they each generally map to one of the 4 types of knowledge described by Anderson and Krathwohl: for example, theoretical tools and quantitative data can broadly be grouped under factual knowledge, fundamental design concepts and criteria and specifications can be grouped under conceptual knowledge, and practical considerations are procedural knowledge.

Anderson and Krathwohl also describe the "cognitive process dimension" in their revised Bloom's Taxonomy. The cognitive process dimension is frequently shown in an hierarchical pyramid shape, as in Figure 3, where learners could be expected to begin with "Remember" which focusses on retention of learning, before moving on to "Understand", "Apply", "Analyze", "Evaluate", and lastly "Create". These latter five levels all focus on transfer of learning, and higher levels will typically include at least some of the earlier levels. For example, "creating" a new software program may require the designer to "analyze" the problem, "evaluate" alternative approaches to solve the problem, and "apply" the syntax rules of the programming language when constructing their solution.

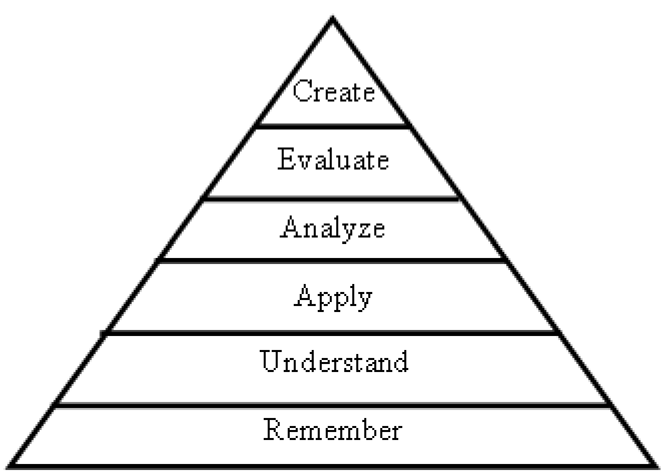


Figure 3 Cognitive process dimension (Anderson and Krathwohl, 2001)

One of the cognitive differences between novice and expert designers is that expert designers have access to a large catalogue of solution "chunks" based on experience and observation. These chunks represent pieces of prior design solutions and ease the demands on working memory while solving a problem (Cross, 2018) (Pretz, et al., 2003). A good example of this comes from the software design domain, where expert programmers have access to a significant mental catalogue of algorithms and past designs to draw on when solving a new problem. These "chunks" of knowledge could represent any of declarative knowledge (e.g., the knowledge of all the different types of valves useful to chemical engineering), conceptual knowledge (e.g., the general relationships between shafts and bearings in mechanical engineering), or procedural knowledge (e.g., the integrative analysis of thermodynamics and fluid flow in a cooling system).

Design processes would exist in the "create" dimension of Anderson and Krathwohl's model as it is concerned with the production of new products, and as such, it requires creativity on the part of the designer. The literature on creativity suggests that creativity is not possible without knowledge. Runco and Chand (1995) in seeking to describe the cognitive processes which are pertinent to creativity, presented a two-tier model of creative thinking. In the first tier are *problem finding*, *ideation*, and *evaluation* processes, and in the second tier are *knowledge* and *motivation* (Figure 4). This model emphasizes the importance of both procedural and declarative knowledge on creativity.

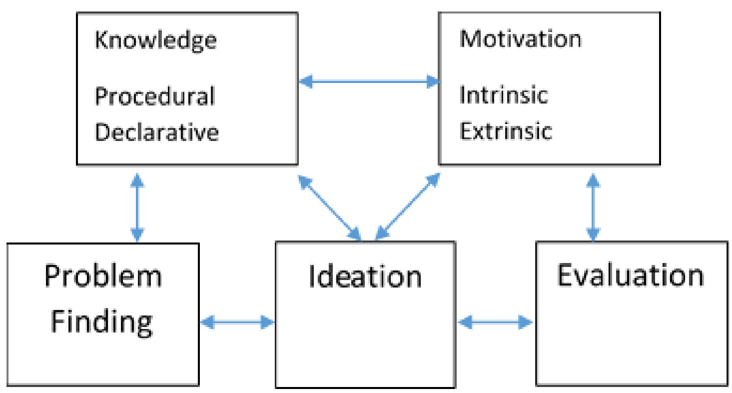


Figure 4 Two tier model of creative thinking (Runco & Chand, 1995)

Amabile (1996) presents a similar componential theory of creativity (Figure 5) which emphasizes the role domain-relevant knowledge and skills have on creativity. While there is some disagreement between these models about when knowledge and motivation are relatively more important to the creative process, in general, they come to similar conclusions. The parallels between the creative process (like those described here by Amabile or Runco and Chand), and the general steps in designing are unmistakable – an observation made by others as well (Howard, et al., 2008).

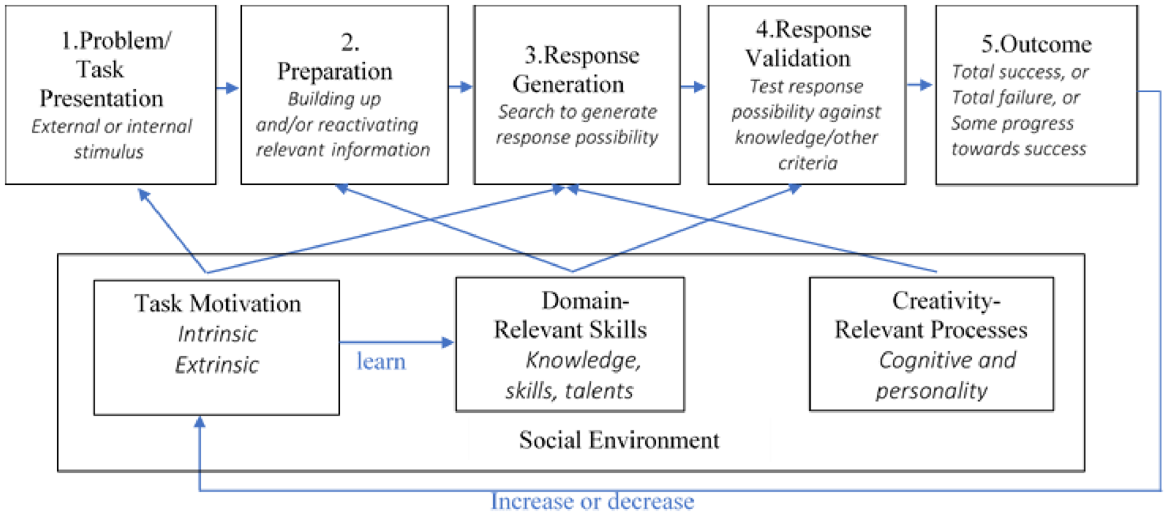


Figure 5 Componential framework of creativity. Adapted from (Amabile, 1996)

Lastly, there is significant evidence from the field of cognitive science that skills such as these can not be easily transferred from one domain to another (far transfer) and can sometimes not even be transferred between different tasks within the same domain (near transfer). Weisberg (2008) took the concept of near transfer and broke it down further. *Problem-specific transfer* is the "nearest" transfer, where a problem-solver is recalling knowledge directly related to the problem at hand (e.g., when a bike designer designs a new bike). *Analogical transfer*, on the other hand is the act of drawing on knowledge from a similar field to solve a problem in a new domain (e.g., a car company designing a bicycle). In Weisberg's view, these types of near transfer happen frequently when solving problems, whereas far (or remote) transfer is unlikely to happen unless there is some match between the remote pieces of knowledge.

Baer and Kaufman (2005) addressed this topic further with respect to design creativity. Baer and Kaufman created a nested "Amusement Park" theory of creativity. In this theory, first you need to meet certain *initial requirements* in intelligence, motivation and environment. Next, a person chooses a *general thematic area* (e.g., the arts or math/science). Within the general thematic area, a person focuses on specific *domains* (e.g., dance vs. music or physics vs. chemistry). Lastly there are *micro-domains* representing specific tasks within the domain (Baer and Kaufman analogize micro-domains as akin to the transition from undergraduate to graduate school: your focus of study narrows as you go deeper). These nested layers to the theory are sorted from the most general skills (initial requirements) to most domain-specific (micro-domains). Baer and Kaufman argue that as people seek to be creative in domains, and then in micro-domains, the required level of domain knowledge (among other things) increases.

Connecting this back to Atman's (2019) and Dorst and Cross' (2001) observations about expert and novice designers, the role of an expert's superior knowledge becomes perhaps clearer. Experts often appear to conduct both a deeper and wider investigation before they begin designing, no doubt based on their greater level of experience in the domain and on what sorts of issues have popped up in past designs. Experts are then able to quickly narrow to the important criteria, limiting the solution space for the remaining designing. Thinking about this from the perspective of a novice, a novice's ability to develop a broad list of design criteria, and a broad set of design concepts will clearly be hindered by their relative lack of knowledge of the field. This begs the question: to what degree is their level of knowledge of the domain responsible for the perceived differences in their design process?

2.2 Personal Epistemology

> *Personal epistemology, or what has also been called epistemic cognition, refers to what individuals think knowledge is and how they think that they and others know. This typically includes how one develops, interprets, evaluates, and justifies knowledge. (Hofer & Bendixen, 2012)*

Perry (1970) through a longitudinal study conducted at Harvard and Radcliffe in the 1950s and early 1960s set out to describe the intellectual development of young adults the way Piaget had for children. Through his methodical study of undergrads of all years, Perry developed a model for what later became known as personal epistemology, or epistemic cognition. Perry's model described a developmental stage model of personal epistemology with nine positions and four stages (summarized in Table 1).

Table 1 Summary of Perry's positions and stages

Position	Description	Beginning of Stage
1-2	Answers are either right or wrong; authorities are the source of "rightness", all others are wrong	Dualism
3	There are multiple answers with no judgment possible; strong reliance on authorities to dictate "rightness"	Multiplicity
4	Certain fields maintain multiple right answers, others can be judged; beginnings of meta-cognition; authorities "want us to think" that relativism exists	
5	Realization that there are no right or wrong answers, only better or worse depending on context; authorities perceived as experts in a domain, a source of knowledge	Relativism
6	In a world of uncertainty, decisions are required, and one must commit to a course of action	Commitment
7-9	Acting on commitments, recognizing implications, dealing with repercussions	

Perry's work is foundational to the study of personal epistemological development and has seen some application to engineering education (Felder & Brent, 2004). Studies within engineering have shown that epistemological stances among undergraduate students may differ based on the domain under discussion (Brown, et al., 2013) (Montfort, et al., 2014); a finding reinforced in other domains (Greene et al., 2010) (Hofer & Bendixen, 2012). Pavelich and Moore (1996) through a series of hour-long interviews with undergraduate students, found most engineering students entering university were in positions 2-3, and that students only progressed an average of one position during their undergraduate career. There is widespread agreement that to be a practicing engineer, one must have developed to the relativism stage (Felder & Brent, 2004) (Pavelich & Moore, 1996); however, several studies of engineering students have found that the majority of undergraduates do not progress beyond position four (Wise, et al., 2001). These interviews sought to understand students' general views on knowledge and truth, and thus were not asking within the context of engineering, nor design, so it is difficult to ascertain how relevant these findings are to the field of engineering design; as Hofer and Bendixen (2012) stated: "As individuals develop increasing expertise within disciplines, they are more likely to understand the varying ways in which knowledge claims are warranted within disciplines".

Building on Perry's work, King and Kitchener (1994) over many years of study developed their model of "reflective judgement". In their words, this model "describes a developmental progression that occurs between childhood and adulthood in the ways that people understand the process of knowing and in the corresponding ways that they justify their beliefs about ill-structured problems". Importantly for our research agenda, King and Kitchener were intentionally looking at student judgement as it pertains to ill-structured problems (though they did not study design, or even engineering problems). Table 2 summarizes the seven levels of the reflective judgement model.
Table 3 presents a comparison between the positions of Perry's model and King and Kitchener's. These models have much in common, and while Perry's model has seen more use in engineering, King and Kitchener's model was developed by studying a more diverse population (Perry primarily studied male undergraduate students enrolled at Harvard in the 1970s), was developed with ill-structured problem-solving in mind, and so moving forwards in this thesis, King and Kitchener's model will be used.

As design experts acquire experience and expertise in their domain, they will repeatedly confront design situations where a solution is not evident, assumptions need to be made based on missing information or differences in interpretation, and where justified decisions will need to be made to continue moving forwards with a design. These design situations are fertile soil for personal epistemological development, and so discipline experts are likely to have epistemic beliefs more in line with the higher positions of the developmental models as opposed to undergraduate students who by and large have not progressed beyond quasi-reflective thinking.

Table 2 King & Kitchener's (1994) Reflective Judgement Model

Stage	View of knowledge	Concept of justification
1. Pre-reflective thinking	Knowledge is absolute and concrete; can be obtained with certainty	Beliefs need no justification; what is believed to be true, is true
2. Pre-reflective thinking	Knowledge is absolutely certain or not immediately available; knowledge is obtained through direct observation or from authorities	Beliefs need no justification, or are justified because they agree with an authority; issues are assumed to have a right answer
3. Pre-reflective thinking	Knowledge is either certain and obtained from authorities, or temporarily uncertain and so only personal beliefs can exist	Beliefs are justified because they agree with authority, or are defended as personal opinion
4. Quasi-reflective thinking	Knowledge is uncertain and idiosyncratic; knowing always involves an element of uncertainty	Beliefs are justified using idiosyncratic evidence/argument
5. Quasi-reflective thinking	Knowledge is contextual and subjective; only interpretations of evidence may be known	Beliefs are justified within a context. Specific beliefs are context-specific or are balanced against other interpretations
6. Reflective thinking	Knowledge is individual conclusions based on information from a variety of sources. Interpretations based on evidence across contexts and on evaluated opinions of reputable others can be known.	Beliefs are justified by comparing different perspectives and by constructing solutions that are evaluated by criteria such as weight of the evidence, or the need for action
7. Reflective thinking	Knowledge is the outcome of a process of inquiry in which solutions are constructed. The adequacy is evaluated in terms of reasonableness or probability based on current evidence and is re-evaluated when new evidence becomes available.	Beliefs are justified probabilistically based on a variety of interpretive considerations. Conclusions are defended as representing the most complete, or plausible understanding of an issue based on existing evidence.

Table 3 Comparison of Perry's model and King & Kitchener's model (Felder & Brent, 2004)

	Dualism	Multiplicity		Relativism	Commitment
Perry	Positions 1-2	Position 3	Position 4	Positions 5-7	Positions 8-9
King-Kitchener	Pre-reflective thinking (Stages 1-2)	Pre-reflective thinking (Stage 3)	Quasi-reflective thinking (Stages 4-5)	Reflective thinking (Stages 6-7)	No equivalent

This more developed epistemic cognition, plus greater factual, conceptual, and procedural knowledge of the domain may explain the behaviour of Cross' "Ill-behaved problem-solvers" and Atman's expert designers who spend more time in problem scoping, and who look at a broader set of design criteria. Looking at this situation from a novice's perspective, when a designer has not developed beyond pre-reflective thinking, why would they conduct a broad search for design criteria, and for possible solutions? In their worldview, problems have a single correct answer, largely dictated by what an expert has told them. For a novice, this could manifest as unthinkingly following the requests of the client even when it will not lead to a good design outcome, or to the development of an easy/obvious solution that is difficult to justify because justification is not yet part of their problem-solving process. Personal epistemology then, may play an important cognitive role in explaining the behaviour of a designer, but the extent to which it contributes to expert-level designing, and its interaction(s) with domain knowledge are not clear.

2.2.1 Developing Student Epistemology in the Classroom

The focus of Perry was on describing the development levels of personal epistemology, nonetheless, he does offer some suggestions for how to create learning environments to develop personal epistemology (Perry, 1970 pp. 214-215). Students need to be presented with incongruities in their way of thinking that promote them moving to higher levels of progression. As they transition, students need support: models of thinking to emulate from instructors, and support of their community. Perry also acknowledges the challenges of encouraging student growth in personal epistemology. Students who have recently arrived in relativism will not be ready to progress beyond that point immediately, and care must be taken at this stage, or a student may “escape” or “retreat” to prior levels, rejecting their growth. Ultimately, Perry recognized that the student is the one that must take the step of progressing, and that this takes courage of a sort: “At each step the student senses [their] option of taking up new responsibilities or of pulling out in retreat or alienation. [They] must make the decision [themselves]”.

King and Kitchener (1994) came to similar conclusions as Perry, though they add some additional thoughts. King and Kitchener posit that people function within a “developmental range” of stages, not within a single stage. King and Kitchener further state that the type of response a person gives depends on the task and its context, pedagogical factors (e.g., clarity of feedback offered), environmental factors (e.g., pressure to compete), and personal factors (e.g., fatigue). They also summarize environmental factors that are useful for promoting development: an instructor who pays attention to the types of intellectual challenges they are creating, including the supports offered, and the clarity of feedback, and an instructor who provides opportunities to practice without fear of failing. Lastly, King and Kitchener state that students need repeated exposure to ill-structured problems throughout their education where they are forced to confront situations where their experience doesn’t match their expectations. When students reflect on these moments of incongruence, it can lead them to challenge their assumptions and can lead to their personal epistemology progressing.

A more recent model which describes how personal epistemology develops is the educational model of personal epistemology (EMPE). The EMPE theorizes there are four components which constitute the "epistemic climate" of a learning environment (Feucht, 2010):

- Students' personal epistemologies
- Instructor's personal epistemology
- Epistemic instructions – epistemic instructions embedded in the teaching methods
- Epistemic knowledge representations – epistemic messages that are embedded in content knowledge such as curricula or books

A more detailed model is Rule and Bendixen (2010) Integrative Model (IM) of personal epistemological development which provides further understanding of the interplays between the personal epistemologies of students and instructors, and the classroom environment (a simplified version of their model can be seen in Figure 6). They theorize that the development from a person's current beliefs to more advanced epistemological beliefs requires three mechanisms of change: epistemic doubt, epistemic volition, and resolution strategies. *Epistemic doubt* occurs when an individual's beliefs about knowledge and knowing are challenged, creating a specific kind of cognitive dissonance. A person experiencing epistemic doubt then requires the *epistemic volition* to act on that doubt. Acting with epistemic volition requires the individual to take ownership of their thinking and exert effort to develop their personal epistemology. Lastly, if the individual has epistemic doubt, and the epistemic volition to change their thinking, they require *resolution strategies* to take the final step towards more advanced beliefs. Rule and Bendixen give some examples of resolution strategies including reflection and social interaction (e.g., discussing with instructor or peers).

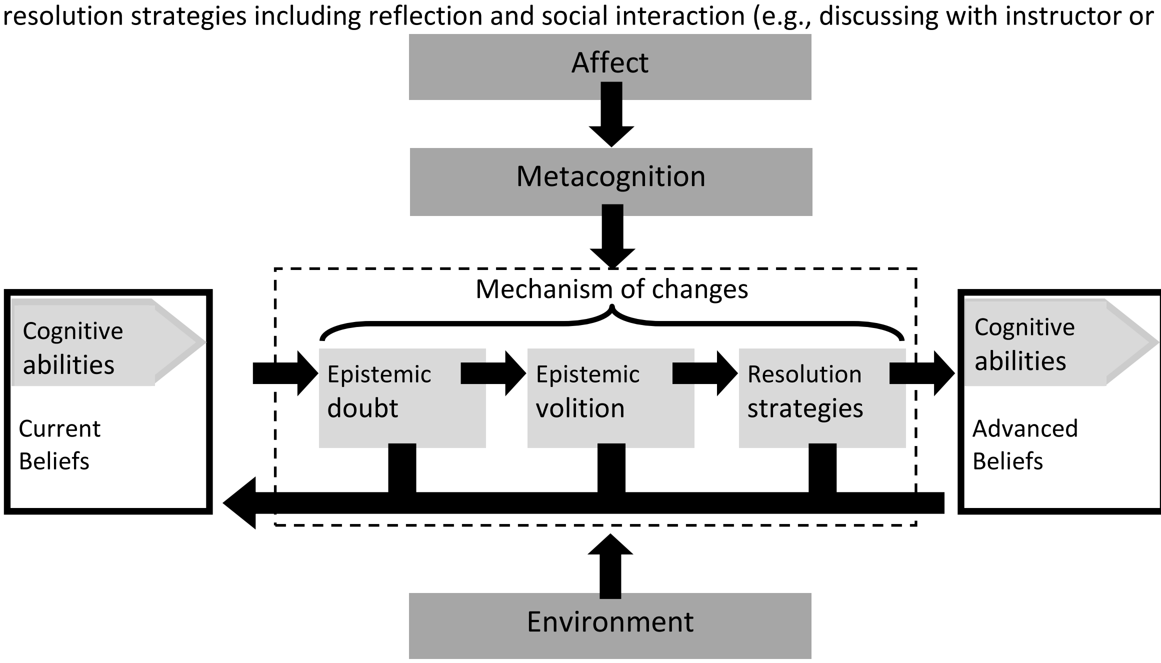


Figure 6 The integrative model for personal epistemology development (simplified from Rule & Bendixen, 2010)

The IM model also describes the mediating roles of metacognition and affect on the mechanisms of change: *metacognition* will enable the steps of epistemic volition and is central to reflection as a resolution strategy, while *affect* can constrain and/or facilitate epistemological development (e.g., one needs the motivation and concentration to possess the epistemic volition to challenge their own beliefs). Lastly, the IM model includes the role of the environment including the epistemic climate of the environment, and the impact of the personal epistemologies of others in the environment. In the full model, the role of peers on personal epistemological development is described as a "multiplier": as people in the environment develop more advanced personal epistemologies, it becomes more likely that epistemic doubt will be triggered in others causing a snowball effect of advancement in the entire population. Clearly the instructor will play a crucial role in the environment as they are best positioned to model more advanced beliefs to the entire group.

With this understanding of design expertise, design problems, and some of the elements present in the designer themselves, the next chapter will discuss strategies for teaching engineering design. Chapter 3 will also discuss the institutional context where this thesis research took place.

3 Teaching and Learning of Design in First Year

To provide a specific context for our research agenda, the Mechanical Engineering (ME) program at Waterloo will be the focus. The choice of Mechanical Engineering allows for easy comparisons to other published studies as it is frequently the subject of design research, and as a single discipline (as compared to multi-disciplinary programs like Mechatronics), design only needs to be examined from one perspective (as opposed to from the perspective of both software and hardware, as in the example of Mechatronics). All Waterloo Engineering students are required to complete a minimum of five, four-month long co-op work terms to graduate starting in first year. This thesis will explore the impact of the first semester of first year (the "1A" semester), and of students' first co-operative work term, on student design skills. Mechanical Engineering students receive their first design instruction in ME 100 (Introduction to Mechanical Engineering Practice I) in their 1A semester. An abridged course description of ME 100 states:

> *This course is focused on fundamental knowledge and skills essential for academic and professional development in mechanical engineering. It covers basic methods and principles used by mechanical engineers, e.g., fundamentals of technical communication, the design process and problem solving, measurements and data analysis, engineering professionalism, safety, and intellectual property. The fundamentals of engineering graphical communication using computer-aided design (CAD) and freehand sketching will be a significant component of this course... Examples are drawn from mechanical engineering.*

In the second semester of first year (the "1B" semester), ME students receive additional design instruction in ME 101 (Introduction to Mechanical Engineering Practice II) from the perspective of both mechanical design, and software design. This thesis will not focus on the teaching and learning that occurs in ME 101; however, it provides a useful measurement point as students are still learning (and thinking about) design, and the students are likely to have received some teaching from ME 101 before they are interviewed in their 1B term.

When engineering programs such as those found at the University of Waterloo are reviewed, engineering design in first year is predominantly taught using two methods: knowledge-based content delivery of what is involved in design (e.g., lectures on the design process), and project-based (and commonly also team-based) learning. It may also be possible to have lab-based settings where design skills are taught or reinforced, though that is not as common in the first year. The design pedagogies employed can be either formative or summative, though summative assessments in the form of a course, or cornerstone, project are more typical. These activities can be augmented with the addition of other summative or formative design experiences, typically of a short duration (e.g. design sprints, or designiettes (Wood, et al., 2012)).

For this thesis, both ME 100 instructors were interviewed to ensure an accurate picture of design teaching is captured. These data provide important context to understand any changes in student design behaviours between their first and second semester and will be presented in Chapter 7. Based on past offerings of ME 100, design lectures, short duration active pedagogies, and project-based learning are frequently employed in the course. The next three sections will provide an overview of how lectures on design, and active design pedagogies like device dissections; course projects; and co-operative work terms could impact student learning of design.

3.1 Design Lectures and Short Duration Activities

While the teaching of introductory design varies year to year as instructors change, there are some generalizations we can make. Historically, the instruction of design in ME 100 has consisted of a few lectures on the design process and how it relates to the discipline. This type of learning has shown to improve student application of the design process, but with limited impact on the quality of the resulting solution (Atman & Bursic, 1996). ME 100 has also taught students how to use 2D and 3D CAD modelling (viz. AutoCAD and SolidWorks). In addition, students participated in several short duration active learning activities throughout the term. These design activities have tended to be well-structured with a focus on specific disciplinary concepts and their role in design. Prince (2004) in a meta-review of active learning in engineering education found that active learning strategies can promote student engagement, and improve conceptual understanding, student attitudes, and retention.

These teaching methods could help develop students' knowledge – factual, conceptual and procedural – and give them a chance to practice designing using a prescribed method. These problems can also begin to expose students to ill-structured and ambiguous situations, to situations with inherent engineering trade-offs, and to problems where there is space for creativity in the generation of design alternatives. Examining these teaching and learning methods through the lens of Crismond and Adams' informed design practice framework, these activities could provide space for students to experience learning while designing, making and explaining knowledge-driven decisions, working creatively to generate design insights and solutions, using design strategies effectively, and integrating and reflecting on knowledge and skills.

3.2 Design Projects

Design projects are likely the most common pedagogy for teaching design. In 1A, ME students take part in a multi-week project in ME 100, which for the past several years has focussed on the design of a new toy for an external, industrial partner (a toy company). This project has an assigned problem domain, but there is significant freedom for students to pursue their own design ideas. Historically, the ME100 course project was ill-structured, albeit with instructional scaffolding in place to support students through the design process. In any ill-structured design problem, students can expect to be confronted with numerous engineering trade-offs– fertile ground for personal epistemological demonstration and development (Felder & Brent, 2004). These projects are also a place for students to apply their classroom learning to new design situations – often requiring them to learn new disciplinary knowledge in the process.

Examining ill-structured design projects through the lens of Crismond and Adams' framework, students in this setting could experience: learning while designing, making and explaining knowledge-driven decisions, working creatively to generate design insights and solutions, perceiving and taking perspectives intelligently, using design strategies effectively, and integrating and reflecting on knowledge and skills; with a possibility of conducting sustained technological investigations. These projects should, therefore, provide an excellent place to develop student design knowledge and skills.

3.3 Design Learning in Co-operative Work Term Settings

Paid co-operative work term experiences have been part of the undergraduate training of engineers since 1905 at the University of Cincinnati and saw rapid expansion to other universities in the United States between 1910 and 1920 (Noble, 1977). When the earliest co-op programs were started, the educators at the time saw an opportunity to embed students in the professional work environment while they were learning the foundations of engineering to improve their training, as "the school… could in no way approximate the actual situation in industry, and only a few of the best schools could even begin to afford up-to-date equipment as existed in industry" (Noble, 1977, p. 185). They felt that this approach would "furnish to the manufacturer a man skilled both in theory and practice" (Noble, 1977, p. 186). The participating companies at the time saw this as a chance to try out students as prospective employees, and also as a means to teach them subjects which they weren't learning in their traditional curricula like management skills and "cost-keeping" (Noble, 1977, p. 189). So, while there was knowledge and skill development happening in these early programs, the co-op placements were also exposing students to the industrial work environment to better prepare them to enter careers there upon graduation.

The first co-op program in Canada was in Engineering at the University of Waterloo and co-op has been a requirement of all engineering programs since the University's founding in 1957 (Associate Provost, Co-operative and Experiential Education, n.d.). Waterloo Engineering requires that all undergraduate students complete at least five, four-month long co-operative work terms before graduation. In first year at

Waterloo, students are sorted in to either “4-Stream”, or “8-Stream”, indicating how many months of instruction those students receive before their first work term (i.e. either four months or one academic term; or eight months or two academic terms, respectively). Programs with large enrolments, like mechanical engineering have one 4-stream class, and one 8-stream class.

Interestingly, even with the long history of co-operative work term experiences in engineering education, there is comparatively little literature that investigates what students are learning in their work term placements; for example, work terms are not included in the discussion of engineering education methods by Sheppard, et al. (2009), though international service learning (a related work-integrated learning method) is mentioned briefly. This is especially noticeable in the design education literature (as highlighted by Litster et al, 2021). In their review of the literature on design work-integrated learning (WIL), Litster et al. (2021) found evidence of:

- students applying design knowledge in work-term settings,
- developing their procedural knowledge of design in WIL settings,
- development of behaviours indicative of informed designers like conducting research, analysing the problem before designing solutions, and making reasoned decisions, and
- develop students understanding of the broader context of professional engineering practice like the societal impacts of design, knowledge of finance and safety, and professional communication skills.

Rennick et al. (2022) in a study of an engineering design-related work term at the University of Waterloo found students were demonstrating graduate attributes relating to design during their work term, and often at levels above their academic progression at the time; indicating an environment which may be conducive to developing these skills. It would be fair to say that co-operative work term environments can provide students with opportunities to learn knowledge related to the professional practice of engineering while also applying their engineering knowledge in the presence of practicing professional supervising their work – an environment which is conducive to acquisition of expertise (Ericsson, 2003).

Applying the integrative model for personal epistemological development (Rule & Bendixen, 2010) to the work term setting, there is a high likelihood of a novice designer experiencing epistemic doubt during their work term as they work on real-world problems in a professional context. What is less clear are the relative levels of epistemic volition and of resolution strategies in the professional work environment. Certainly, students have more time to reflect on their work in a full-time co-operative work term environment than in a typical academic term where they may be taking five or more courses simultaneously. This additional time and focus could have a positive effect on the presence of metacognition in this environment, which would assist the student with mustering their epistemic volition. For resolution strategies, students in a work term setting may have supportive managers or co-workers who could assist, and/or students may have developed useful resolution strategies in their academic work that they can then transfer to the work environment, but these may not be universally present – differences from student to student and work setting to work setting will certainly be present. For affect, generally work-integrated learning settings have been found to develop student confidence in engineering skills and develop student professional identity (Litster, et al., 2021). The nature of work assigned to a novice engineering student in a co-op environment could range from engaging, ill-structured design problems to repetitive, low-skill work tasks, perhaps limited growth opportunities.

This discussion on informed/expert design behaviours, the role of knowledge and personal epistemology in problem-solving and designing, and on how knowledge and personal epistemology develop and are taught, reveals the purpose of this thesis research. The purpose of this thesis research is to explore the individual differences in novice designers, the extent to which early university-level training in design changes or improves these behaviours, and the extent to which this training might impact the students themselves. This thesis will focus on the related constructs of knowledge and personal epistemology, how they interact, and how individual differences in these constructs manifest in different design behaviours.

The next chapter will describe the research plan including research questions, data collection, and analysis methods.

4 Research Plan

From the discussion in Chapter 3, students in their first year of mechanical engineering at Waterloo are provided a number of opportunities to develop design expertise. What is unclear, however, is the impact of this varied design instruction on the underlying cognitive structures of students, and how these structures manifest as "good designerly behaviour" as described by Atman (2019). This thesis sought to investigate the relationship(s) between first-year design instruction (including work-integrated learning), knowledge, personal epistemological development, and design behaviour.

Past research has investigated the impact of design teaching on design behaviours; for example, Atman and Bursic (1996) investigated changes in design behaviour after novices read a design textbook, and Atman et al. (2005) investigated the differences in design behaviour between first- and fourth-year engineering students – research which included 18 longitudinal participants who took part in the study in both their first and fourth years. Examination of the interactions between knowledge and personal epistemological development, and between personal epistemological development and design behaviours have received little attention, however. Similarly, the interactions between all three of knowledge, personal epistemology, and design behaviour have received little to no attention. It is these intersecting constructs that will be investigated in this thesis. Due to the scarcity of past research on these various intersections, research questions (as opposed to propositions or hypotheses) were selected as the primary investigative framing of this thesis to keep the researcher as open to emergent findings as possible.

To investigate these relationships, the following three research questions were investigated:

> **RQ1**: What effect(s) do knowledge and personal epistemology have on novice designers' design behaviours?
>
> **RQ2**: What impact does one semester of design instruction have on novice designers' knowledge, personal epistemology, and design behaviours?
>
> > **RQ2.a**: What is the extent of this impact after one month? After five months?
>
> **RQ3**: What is the interaction between knowledge and personal epistemology while designing?

Yin (2018) states that "exploratory studies may have a legitimate reason for not having any propositions… however [they] should still have some purpose". In this thesis, the purpose is clear, and application of existing tools to deductively analyse the data will assist with providing direction to the study.

4.1 Data Collection Methods

The research design selected for this thesis is a multiple (or collective) case study which sought to illustrate relationships between knowledge, personal epistemological development, and design behaviours in novice engineering designers. Case study approaches are useful for conducting in-depth analyses of cases, and for comparisons of several cases (Creswell & Poth, 2018); both of which are important to this thesis. The methodology used was an exploratory case study approach, not descriptive or explanatory (Yin, 2018). As noted by Yin, exploratory forms of case studies are useful when the situation is initially studied without any prior basis for investigating causality.

The narrative strength of in-depth case study research is ideal for this exploratory work. While the tools for understanding the knowledge domain in teaching and learning environments are relatively robust, with a long history of use – as with Anderson and Krathwohl (2001) – as are the tools for analysing design process and process quality – as with Atman's design timelines (2019), and Crismond and Adams (2012); the tools for in situ understanding of personal epistemology in the design context do not have the same history of use. The high level of detail present in case studies – using data collected from multiple sources – aided the rigor of this thesis, especially where there was novelty in the analysis method employed. The strength of case study research in comparing several cases was important in identifying patterns across student development, both in time and from student to student.

The primary participant pool in this thesis consisted of first year students from mechanical engineering (ME) at the University of Waterloo. Purposive sampling was used to select an approximately equal number of participants from each of 4-stream and 8-stream (with a target of five from each). Interviews were conducted with student participants near the start of both their 1A and 1B terms. For 8-stream students this was in approximately September and January, and for 4-stream students, this was in September and May (after they returned from their first work term). In addition to the student participants, the ME 100 instructor(s) were interviewed at the end of the 1A term to collect detailed information on design instruction in the term. The design courses, work terms, and timing of interviews in first year ME, is summarized in Figure 7.

The flow of the study was as follows:

- The 1A interview served as a baseline measurement of the student's background and design ability. These interviews were completed as close to the start of the 1A term as possible to limit the impact of 1A design instruction on the baseline measurement.
- The students completed ME 100 as normal

- The ME 100 course instructor(s) were interviewed once lectures ended to capture details on how design was taught and assessed during the term
- The 1B interviews inquired about the impact of the 1A term, and the first work term (4-stream students only) on student knowledge of mechanical engineering design, personal epistemological development, and design ability. These interviews were conducted as close to the beginning of 1B as possible to limit the impact of the additional design instruction participants would receive in ME 101.

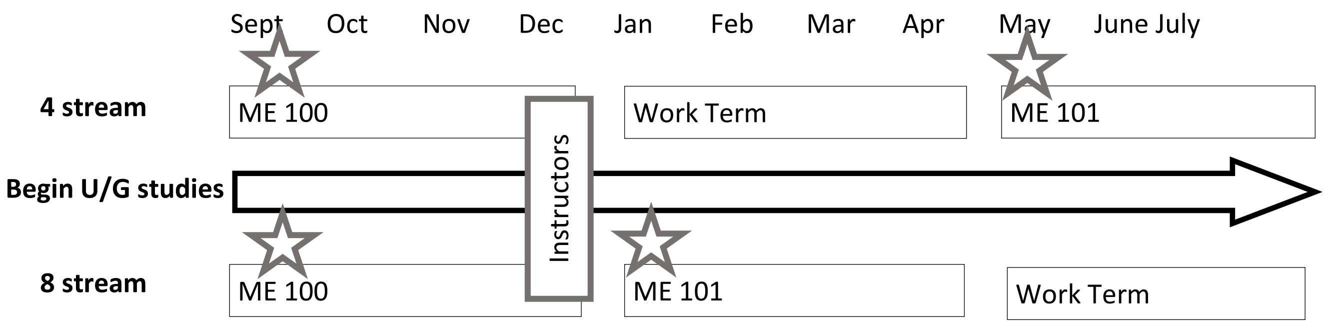


Figure 7 Timing of design courses, co-op work terms, and interviews in first year ME (student interview timing indicated with stars)

Consistent with best practices for multiple case study research designs (Creswell & Poth, 2018), a common interview approach was used for each student interview, and a common analysis approach was used for each case. The interview approach will be explained first, and the analysis approaches will be explained in more detail in section 4.2.

Interviews with students had three phases: a demographic and background information interview; a concurrent think-aloud design exercise where students were asked to design a solution to a mechanical engineering problem; and a retrospective interview to elicit deeper insights into their thinking, in the context of the design problem they just solved. Table 4 provides a summary mapping of interview sections to construct under investigation. Table 4 also summarizes how each interview section was analysed with the thesis chapter where the analysis is presented.

Table 4 Mapping of interview sections to constructs under investigation

Interview Section	Construct	Analysis Method	Thesis chapter
1A student background	1A knowledge	Anderson & Krathwohl (2001)	5
	1A personal epistemology	King & Kitchener (1994)	9
1A verbal protocol	1A design behaviours	Atman & Bursic (1998) Crismond & Adams (2012)	6
1A retrospective	1A personal epistemology	King & Kitchener (1994)	9
Design course instructors	1B knowledge	Anderson & Krathwohl (2001)	7
1B student background	1B knowledge	Anderson & Krathwohl (2001)	7
	1B personal epistemology	King & Kitchener (1994)	9
1B verbal protocol	1B Design Behaviours	Atman & Bursic (1998) Crismond & Adams (2012)	8
1B retrospective	1B personal epistemology	King & Kitchener (1994)	9

All interviews took place online to comply with Covid-19 restrictions, and to enable video recording and transcription. The full interview protocol for students is available in Appendix A, and for instructors in Appendix B, but the interview structures will be summarized next. Analysis methods are summarized in section 4.2.

4.1.1 Background Interview

In 1A, the demographic and background information section sought to capture a holistic view of past design experience as a means for describing the participants' existing knowledge and experience of design. For the 1B interview, the background section asked students about their design experience(s) while in 1A from curricular, and both structured and unstructured extra-curricular experiences (e.g., from student design teams). For 4-stream students, they were also asked about the experience they gained during their first work term. These questions sought evidence of whether students applied what they had learned in 1A, their opportunities for knowledge development prior to 1B, as well as characterize whether any of their experiences aligned with recommendations for promoting personal epistemological development.

The questions were ordered to capture details of structured design training before moving to progressively less structured opportunities. In this thesis, activities with the most structure included courses, extra-curriculars with instructional/mentoring components, and professional work experience. Less structured activities included competitions (e.g. hackathons, FIRST Robotics competitions, etc.), where mentoring may or may not be present, but there is virtually no formal instruction occurring. Examples of the least structured activities were self-driven activities like hobbies or learning through online videos/tutorials.

Differentiating between structured and unstructured training is important to investigating development of the participants' different forms of knowledge, and their personal epistemologies. For knowledge, structured opportunities are more likely to include training/instruction in procedural knowledge and may have additional opportunity for meta-knowledge to develop as many structured design activities for high school students feature some sort of reflection as part of the activity. However, both structured and unstructured design experiences have the capacity for developing participants' factual, conceptual, and procedural knowledge of elements of mechanical engineering. For personal epistemology, as outlined in Section 2.2.1, personal epistemology develops best through a coaching/mentoring process with informed teachers, which is much more likely to occur during structured design training, than self-driven and/or unstructured practice.

4.1.2 Verbal Protocol

Verbal protocols are a common method for studying problem-solving expertise (Feltovich, et al., 2018), with well-documented uses in the design literature over the past three decades (Litster & Hurst, 2021). For this thesis, the concurrent think-aloud design exercise provided an opportunity to observe student design behaviour and enabled an analysis of student design process as described by Atman and Bursic (1998). As recommended by Ericsson and Simon (1996), students participated in a warm-up exercise prior to beginning the design exercise to practice the verbal protocol. This ensured they understood expectations for the design problem and aimed to make them more comfortable with what was to follow.

The design problems themselves drew from past studies of design (Litster & Hurst, 2021), and consisted of two problems: a device which enables a user to open a screw-top jar one-handed (for the 1A interviews), and a device which helps a user to open a stuck double-hung window (for the 1B interviews). These design prompts were selected as they can be solved with entirely mechanical devices (or could include electro-mechanical elements if so desired), were simple to communicate, involving everyday items with which students were likely to be familiar, and were feasible to be solved in 90 minutes.

4.1.3 Retrospective Interview

During the retrospective section of the interview, student participants were asked a series of questions about the design exercise. These questions sought evidence relating to their personal epistemological development, and their use of past engineering and/or design learning while solving the problem. King and Kitchener (1994) proposed that reflective judgement manifests in a person's view of knowledge, and concept of justification. For this thesis, the retrospective portion of the interview was important for discerning their personal epistemological development as the design exercise provided fertile ground to discuss decision-making, and consequently their justifications for those decisions.

During the design activity, students had permission to search out any information they liked online. Through these searches, and their comments while they examined online material, it was sometimes possible to assess their views on the value or usefulness of the knowledge they found, and its relative worth to design. To capture details of online searches, students were asked to either share their screen so the interviewer could follow what they were looking at, or to describe their online search verbally.

Lastly, the problem was presented as though the students were employed by a company on their co-op work term, and so the retrospective interview included a question about how they would justify their design decisions to their boss in a professional environment. This discussion helped illuminate how they viewed the role of an authority in their decision-making while designing.

4.1.4 Instructor Interview

Interviews with the ME 100 course instructors took place in early December once lectures had ended. ME 100 does not have a final exam, so all course assessments were collected at that point, giving the instructor a chance to reflect on the entire term. The questions during these interviews captured details on the factual, conceptual, and procedural knowledge of design taught in the course, details and timing of any design assessments given to students, and details on the epistemic climate of the course. All student participants were enrolled in this course, and so the instructor interviews captured details on the formal design instruction which took place, allowing the 1B student interviews to focus more on other places/modes of design learning (e.g., student design teams, work terms, and/or personal projects).

4.2 Data Analysis Methods

As is typical of case studies with multiple cases (Creswell and Poth, 2018; pg. 100), analysis took place at two levels: within-case, and cross-case. For the within-case analysis, the three sections of the interview were analysed separately before integrating into a coherent whole (starting with knowledge before transitioning to personal epistemology). The analyses presented in this exploratory case study thesis were primarily deductive in nature. This thesis used existing tools/frameworks for understanding knowledge, design behaviour, and personal epistemology to seek deeper understandings of relationships between the three constructs. This is somewhat atypical for exploratory case studies, but due to the lack of prior research connecting these constructs in the context of engineering design, some direction for the analyses of the cases was required. As Yin (2018; pg. 28) explains, even exploratory case study research needs “some rationale and direction, even if [the] initial assumptions might later have been proved wrong”. In this way, the deductive application of existing tools provided a direction to apply structure to the collected data.

Different coding strategies were used for developing the initial understanding of the data primarily based on the level to which the respective theory had been operationalized for this type of coding. Anderson and Krathwohl (2001) and Atman & Bursic (1998) have operationalized their codes in detail, enabling a more straightforward *Protocol Coding* (Miles, et al., 2020). Protocol coding is used in cases where there is a preestablished or prescribed system. Protocol coding was appropriate for this thesis because both Anderson and Krathwohl (2001) and Atman & Bursic (1998) were used in the context for which they were designed (viz. understanding the knowledge dimensions embedded in educational activities, and analysing verbal protocols of design activity, respectively). In some cases, the codes needed to be modified or clarified slightly, which will be described in detail in sections 4.2.1 for Anderson & Krathwohl, and 4.2.2 for Atman & Bursic. In applying Crismond and Adams (2012) to understand design process quality, *Holistic Coding* was employed (Miles, et al., 2020). Holistic coding is applied to large units of data to capture a big picture view of the contents. According to Miles et al. (2020), “holistic coding is most applicable when a researcher has a general idea of what to investigate in the data”. To facilitate this approach in this thesis, the Informed Design Teaching and Learning Matrix was adapted into a series of behaviours which could then be coded. These codes will be elaborated on in section 4.2.3. Lastly, *Concept Coding* was employed to interpret the data relating to personal epistemological development for the student participants. Concept coding is a means of describing observable behaviours with ideas (Miles, et al., 2020). The unit of analysis for concept coding can be large units of data; for the coding of personal epistemology in this thesis, it was typically limited to one participant response to a question (though occasionally there was an interviewer follow-up to get the participant to clarify their comment). These codes will be elaborated on in section 4.2.4.

Inductive analysis was used concurrently to identify any important themes in the students’ responses that were not captured by the deductive methods previously described, as well as to document evidence that may be contradictory to other findings. As described by Creswell and Pohl (2018), inductive analysis is an important counterbalance to the predominantly deductive methods employed, ensuring that significant findings were not ignored simply because they didn’t fit the existing tools applied in this thesis. *Concept coding* was used to apply meaning to the passages, and to identify trends across the cases. As with coding for epistemological development, the unit of analysis for the inductive concept coding was typically limited to the response from the participant to one question from the interviewer.

With an initial understanding of the data developed through the coding strategies just described, another cycle of cross-case analyses was completed to examine relationships between the codes, between the cases, and over time. The cross-case analyses were conducted last and sought to characterise any patterns in the data across the cases, as well as to describe the similarities and differences across the cases. Conceptually clustered matrices and network displays (Miles, et al., 2020) were the primary methods used to explore connections between knowledge, personal epistemology, and design behaviours; however, thematic analysis of inductively-coded data was also conducted to summarize other related or contradictory findings.

Memo-writing, a critical component of grounded theory qualitative research, was conducted throughout data collection and analysis (Creswell & Poth, 2018). These memos captured the thoughts and observations of the researcher during all phases of data collection and analysis and were used to confirm and direct later analysis steps with earlier ones. While this thesis is case study-based, and so not grounded theory research, memos were used to direct researcher attention and ensure accuracy as analyses moved through the various inductive and deductive phases.

In summary, the background sections of the student interviews were analysed deductively by applying both the knowledge and cognitive process dimensions from Anderson and Krathwohl (2001). The design processes from the design activities were first described using the design timeline (Atman & Bursic, 1998) before the behaviours were analysed using Crismond and Adams (2012). The retrospective sections of the interview were analysed to ascertain the personal epistemological development of the student using King and Kitchener's model (1994). Inductive coding was also used to capture other emergent findings. The next sub-sections will present additional detail on the coding strategies used in this thesis, beginning with the deductive coding (knowledge, design process, process quality, and personal epistemology), followed by the inductive coding strategies, and ending with a brief discussion of the cross-case analysis methods.

4.2.1 Knowledge Coding - Student Participants

The data used for knowledge coding of student experience in both the 1A and 1B participant interviews came from the "background interview" portion of each interview (see section 4.1.1 for more detail). This was the first section of both the 1A and 1B interviews with each student participant and can be seen in full in Appendix A under the labels "1A Experience Questions", and "1B Experience Questions".

As explained in the previous section, protocol coding (Miles, et al., 2020) was the approach taken, using Anderson and Krathwohl's knowledge and cognitive process dimensions (Anderson, et al., 2001). Other theoretical approaches to categorizing knowledge were considered, including the knowledge categories outlined by Jonassen (2000) in the "individual differences of his model" (viz. structural, conceptual, procedural, and domain-specific knowledge), and the eight knowledge categories described by Sheppard et al (2009). These other knowledge classification schemes have not been operationalized in this type of research to the extent of Anderson and Krathwohl, however. Sheppard's categories, in particular, have not been used in this way, and were intended as a comprehensive summary of all the types of knowledge an engineer might possess across engineering tasks, knowledge types, and domains. For Jonassen's categories, there is significant overlap with Anderson and Krathwohl's knowledge dimension, and ambiguity around Jonassen means by domain-specific knowledge, and how it differs from structural, conceptual, and procedural knowledge; and so Anderson and Krathwohl was deemed the more appropriate choice.

The unit of analysis for this coding was by experience as described by the participant. This coding focussed on the knowledge dimensions of factual, conceptual, and procedural knowledge; and has omitted metacognitive knowledge. Understanding participant metacognitive knowledge development would have required dedicated questions to collect data on this construct. The cognitive process dimensions from Anderson and Krathwohl were applied to the student experiences as a means of describing the complexity of application for each knowledge category. In this coding, the highest cognitive complexity of tasks relating to each knowledge construct were selected to describe the way(s) in which the student had mobilized this knowledge in past experiences.

Table 5 Knowledge development from background experiences – Sample from Chris in 1A

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Limited knowledge of terminology of automotive domain	Interest in professional car racing; online videos and experience with DIY vehicle maintenance	2. Understand - Summarizing
Conceptual	Limited knowledge of components in automotive domain	Online videos and experience with DIY vehicle maintenance	3. Apply – Executing.
Procedural	Limited knowledge of automotive-specific skills, techniques	Online videos on DIY vehicle maintenance	3. Apply – Executing.

The coding process is best illustrated with an example; Table 5 is a partial reproduction of Chris' knowledge from the 1A interview. The process for coding the knowledge and cognitive process dimensions began with the identification of an experience (or related set of experiences). In his interview, Chris described two related experiences: an interest in the automotive domain including professional car racing, and some experience with simple DIY vehicle maintenance. The domain for Chris was therefore identified as "automotive". The researcher then went through each knowledge type and analysed the knowledge that experience might have cultivated in that domain. For example, in the factual knowledge category, Chris could be expected to have familiarity with the components present in cars, especially the components which are highly visible, require regular maintenance, or are frequently discussed in professional racing (e.g. tires, brakes, fluids like oil, etc.) In the conceptual knowledge type, Chris could be expected to have familiarity with vehicle systems that related to these components (e.g. the oiling system, braking system, aerodynamics, etc.) Lastly, the procedural category was assessed. In this category, the researcher was capturing participant knowledge of processes (e.g. manufacturing processes, maintenance processes, etc.) that relate to the domain and the experience. For example, because Chris had experience changing the oil on his personal car, he possessed knowledge that related to the processes of maintaining the engine oil system in the car. It is important to note that not all experiences described by participants in this thesis had connections with all three knowledge types, though this example of Chris just described, did.

With the knowledge types identified and listed, the level of knowledge was described. Only two levels were used: "limited" knowledge for cases where the student had only limited experience in the domain and no structured learning opportunities; and "knowledge" of the domain if the student had more experience (e.g. from a high school class, a guided extra-curricular experience, work experience, etc.), and more depth of experience (i.e. longer engagement with the domain). For Chris' example, his automotive domain knowledge (of all three types) was limited, as it was self-taught through TV programs and online videos, and his practical experience with vehicle maintenance had a narrow focus.

The final component of the knowledge summarized in Table 5 was the cognitive process dimension. In this assessment, the researcher identified the most complex cognitive process that the student may have employed based on the description of their experience, giving the student the benefit of the doubt. For example, through Chris' DIY vehicle maintenance experience, he *applied* his knowledge of the engine oiling system, and his knowledge of vehicle maintenance to change the oil in his car.

The last analysis step for the knowledge types presented for each case was an overall assessment of level of knowledge, and relevance of the domain to mechanical engineering for the cross-case analysis. For both level, and relevance, three levels were used: low, medium, and high. To assess the level of knowledge, the level codes were described as:

- Low: level of experience in domain classified as "limited" and cognitive process limited to the lowest four levels: Remember, Understand, Apply, or Analyze
- Medium: level of experience in domain classified as more than "limited", but lack of structured/supervised learning in domain and/or short duration of experience
- High: level of experience in domain classified as more than "limited", and presence of structured/supervised learning and/or long duration of experience

To assess the relevance, a comparison to the curriculum of mechanical engineering was made, and the codes were described as:

- Low: domain included/assessed in one or fewer courses in curriculum (e.g. electric circuits are included in a single first-year course in mechanical engineering at Waterloo)
- Medium: domain included/assessed in more than one course, but is not the subject of dedicated instruction (e.g. 3D printing is commonly used in prototyping in design courses, but is not taught in the curriculum)
- High: domain is the subject of dedicated instruction in curriculum, and/or mechanical engineering careers in domain are commonplace (e.g. there are few/no dedicated courses on the automotive and aerospace domains at Waterloo, but they commonly show up in examples, are present in extra-curricular activities, and are common domains for mechanical engineers to be employed)

Analysis of each student's knowledge from the 1A interview will be presented in Chapter 5, and analysis of each student's knowledge from the 1B interview will be presented in Chapter 7. The connections between knowledge and design behaviours will be explored in Chapters 6 and 8 for 1A and 1B, respectively.

4.2.2 Design Process Coding

The data used for design process coding came from the verbal protocol section of the 1A and 1B student participant interviews (see section 4.1.2 for more detail). As mentioned before, the students were given a protocol analysis warm-up problem first, to gain some familiarity with thinking aloud while they solved problems. The full description of this portion of the interview can be seen in Appendix A under the label "Protocol Analysis Main Problem".

To quote Gero and McNeill (1998): "Protocol data is very rich but unstructured. In order to obtain a detailed understanding of design processes it is necessary to project a framework on the data." Given the narrative case study-based approach in this thesis, to summarize and communicate the design process, a method was needed which had both narrative uses, and which provided opportunities for deeper understanding and analysis. There are a small number of approaches which have been used extensively in the design literature including Atman's timelines (Atman, 2019), Gero's FBS method (Gero & Kannengiesser, 2004), and to a lesser extent, linkography (Litster & Hurst, 2021). The FBS method, which stands for function-behaviour-structure describes eight processes that are fundamental to designing, and while it is a powerful tool for analysing the content of design protocols, it lacks any narrative power in describing that process to the reader and is challenging to learn and use. Atman's design timelines (which are summarized in section 1.1) were selected as the analysis approach as they have the most extensive use in the engineering design literature, can be analysed qualitatively or quantitatively, and are useful as a narrative tool, as is evidenced by their increasing presence in new pedagogies for teaching design (Atman, 2024).

The first step in analysing the design activity portion of the interview was to construct a design timeline for each interview using the codes described in Atman and Bursic (1998). Microsoft Excel was used to construct each timeline. These timelines convey what occurred during the design activity and can be compared against the known behaviours of experts (e.g. from Atman, 2019) to help describe the quality of design process. The original description of the codes from Atman and Bursic, as well as examples of observed behaviours from this thesis are summarized in Table 6. Sample behaviours were included in Table 6 where they demonstrated specific behaviours which supplemented the descriptions provided by Atman and Bursic. Off-topic conversations and breaks were not coded and will show up as sections of the timeline where no design activity is occurring. This is not to say that the participant was not thinking about some aspect of the design but reflects a section that can not be coded as a specific step in the process. Generally, these off-topic conversations were rare, but are described where necessary. The unit of analysis for this deductive coding process was participant utterance with a minimum length of time of one second.

Construction of the timelines necessitated examining both the transcript as well as the video recording to accurately capture the context of the participant behaviour. For example, nearly all the participants used sketching at some point while designing, but the act of sketching represented different design steps at different times. Sketching was used to generate ideas, to model details of a design, as well as to communicate the design to others, and so a combination of what was said, what the participant was doing, as well as the context (what happened before, and what happened after) were required to understand which step in the design process the participant was thinking about. Sketching was one of the more challenging behaviours to code as participants frequently stopped talking out loud while they sketched, and so the act of sketching was often not able to be situated in a particular step until they started talking again and described what they had just done.

Table 6 Codes used in design timeline construction (Atman and Bursic, 1998)

Design Step	Codes (Atman and Bursic, 1998)	Example Observed Behaviour(s)
Problem Definition	Define what the problem really is, identify constraints/criteria, reread problem statement or information sheets, question the problem statement	Listing device requirements, making assumptions about capability of user
Gather Information	Searching for and collecting needed information	Internet search for existing designs, research on design component(s), examining objects that are near to hand
Generate Ideas	Develop possible ideas for a solution, brainstorm, list different alternatives	Creating list of alternatives, concept sketches
Modeling	Modeling, describe how to build an idea, how to make it, measurements, dimensions, calculations	Dimensioned sketching, specifying materials
Feasibility Analysis	Determining workability, verification of workability, does it meet constraints, criteria, etc.	Pantomiming device operation, stepping through operation of device
Evaluation	Comparing alternatives, judgment about different options, is one better, cheaper, more accurate	
Decision	Select one idea or solution among alternatives	Eliminating concepts from future consideration
Communication	Define the design to others, write down a solution or instructions	Creation of refined sketch of device, writing out instructions for device operation, presenting device concept

Once the timelines were constructed, a second phase of analysis took place that was largely descriptive in nature. Each interview was rewatched and sections of the design activity were summarized. The goal of grouping a section of design activity into one coherent “block” was to ease the communication and description of each student’s overall process by providing a clear connection between the descriptive case text and the timeline diagram. These blocks of time demonstrate a coherent block of thinking and could be very short (on the order of seconds of time in the design activity) but were typically on the order of 5-10 minutes. Blocks longer than 15 minutes were exceedingly rare and were typically a sign of a student who had lost control of their process, or who was struggling to finish a task. The start of a new block was identified when the student transitioned into either:

- a different design task (i.e. transitioning from working on one concept solution to a different concept solution), or
- a different type of design activity (e.g. transitioning from modelling of a solution to online research of manufacturing methods).

Where appropriate, when a participant made an explicit connection with their knowledgebase, this was highlighted to enable connections back to their prior experience.

Description of the 1A design timelines will be presented in Chapter 6, and description of the 1B design timelines will be presented in Chapter 8. Chapter 6 and 8 will also make connections to relevant knowledge constructs from each student from the analyses presented in Chapters 5 and 7, respectively.

4.2.3 Design Process Quality Coding

As with the design process coding described in the previous section, the design process *quality* coding relied on data collected in the verbal protocol section of the 1A and 1B student participant interviews. Analysis of design process quality built on the design process coding described in the previous section, and was presented through two lenses: analysis of the design timeline features of experts (Atman, 2019), and analysis using the informed design teaching and learning matrix (Crismond & Adams, 2012).

As described in section 1.1.2, in summarizing two decades worth of studies using design timelines, Atman (2019) found that compared to first year students, graduating students were more likely to:

- engage in decision and communication steps,
- engage in more transitions across steps,
- gather information on a broader set of issues, and
- create higher quality products;

Atman (2019) also found that experts were more likely to:

- spend more time solving the process,
- delay modeling until later in the process,
- gather more information on a broader set of issues, and
- consider a larger and broader set of objects as they were designing.

While the data set in this thesis did not include graduating students or expert designers; these markers of expert design behaviours were nonetheless useful in describing the quality of the process the student participants demonstrated in their interview. To summarize the performance of each participant in this thesis on these dimensions of performance, the following measures were calculated and/or presented:

- the total time spent designing as well as the average (and standard deviation) of time spent by all participants in each round of interviews
- the number of transitions across design steps as well as the rate of transitions
- the percentage of total design time spent in each of the design process steps that appear in Atman's design timelines

The "cascade" shape that describes the ideal design process envelope will also be superimposed on the design timelines to provide a visual indication of the degree to which the participants were behaving like experts. This thesis will not comment on the quality of the end solution that each student generated, as it is challenging to determine a universal set of evaluation criteria which could be objectively applied to all potential solutions. Instead, this thesis briefly commented on the general plausibility of the concept as a real device, as well as the absence/presence of sufficient detail in the design to facilitate manufacturing a prototype of the concept.

To investigate the quality of each participants' design process, Crismond and Adams' Informed Design Teaching and Learning Matrix (2012) was used to summarize the features of each design process (see Table 7 for a summary of the Matrix). These patterns were used in the analyses for each participant to understand to what extent they were (or were not) behaving like beginning vs. informed designers.

Table 7 Patterns of behaviour for different design strategies. Adapted from Crismond and Adams (2012)

Design strategies	**Beginning designers**	**Informed designers**
Understand the challenge	Treat task as well-defined, straightforward; prematurely solve	Delay making decisions to explore problem
Build knowledge	Skip doing research or build solutions immediately	Investigate the problem, how the system works, and prior solutions
Generate Ideas	Work with few or just one idea; design fixation common	Actively conducts divergent thinking to come up with lots of ideas
Represent Ideas	Ideas are superficial, don't reflect deep inquiry, would not work if built	Use multiple representations to explore/investigate ideas, deeper inquiry into how system works
Weigh options and make decisions	Decide without weighing all options; ignore trade-offs of favored design	Multiple methods used to weigh benefits and trade-offs before deciding
Conduct experiments	Do few or no tests on prototypes, run confounded tests	Conduct valid experiments to learn about problem and solution
Troubleshoot	Unfocused way to view prototypes during testing and troubleshooting	Focus attention on problematic areas and propose ways to fix
Revise/Iterate	Design haphazardly, minimum learning taking place, linear design steps	Managed process; iteration and feedback improve ideas; strategies used multiple times
Reflect on process	Little self-monitoring while working, or once finished	Practice reflective thinking, keep tabs on thinking/strategies while working and once finished

Table 8 summarizes the informed design strategies from Crismond and Adams with the design behaviours that were coded for this thesis. In general, conducting experiments and troubleshooting were not expected as the design deliverable was a pen and paper design, and so behaviours related to these strategies were not included in this analysis. Presence of one of the behaviours was either indicated as “Present, but limited”, or “Present”. The limited category was used when the student exhibited part of the behaviour, exhibited the behaviour for a short duration, and/or to give the benefit of the doubt to the student where ambiguity existed in the verbal protocol (perhaps due to bad recording quality, or the participant stopped speaking). For example, Michelle’s research of the problem space in 1A was categorized as present, but limited. In her case, the only research of the problem space conducted was to determine the direction of rotation to loosen a jar lid, which clearly does not capture the full pattern of an informed designer who does “investigations and research to learn about the problem, how the system works, relevant cases, and prior solutions” (Crismond & Adams, 2012).

Table 8 Student behaviours mapped to informed design strategies

Strategies	**Behaviour(s)**
Understand the challenge	State explicit design goals
	Research problem space
Build knowledge	Research solution space
Generate ideas	Generated range of concepts/ideas
Represent ideas	Created detailed drawings and/or models
Weigh options, make decisions	Weigh benefits/trade-offs before making decisions
Conduct experiments	---
Troubleshoot	---
Revise/Iterate	Revisited/re-evaluated design goals
Reflect on process	Evaluated solution against design goals

The behaviours summarized in Table 8 were identified after the analyses of student knowledge, the construction of the design timelines, and after analysing the ME 100 instructor interviews. Completing these analyses first enabled the identification of behaviours that were consistent with what the students were demonstrating in the design activity and consistent with what was taught in ME 100. In addition, the goal was to identify one behaviour for each of the informed design strategies in Crismond and Adams (2012). Ultimately, the “Understand the challenge” and “Build knowledge” design strategies were split into three behaviours: stating explicit design goals, researching the problem space, and researching the solution space. Having two distinct research behaviours was necessary due to the lack of student familiarity with the 1B problem domain (viz. double hung windows). This will be elaborated on in Chapter 8.

The design process quality analyses will be presented in Chapter 6 for the 1A verbal protocol, and in Chapter 8 for the 1B verbal protocol.

4.2.4 Personal Epistemological Development Coding

The data used for coding personal epistemological development came from the background and retrospective interview sections of the 1A and 1B student participant interviews (see section 4.1.3 for more detail), with data collected in the verbal protocol section used to triangulate the coding.

As stated previously, King and Kitchener's Reflective Judgment Model (1994) was the theoretical lens used to interpret personal epistemologies from the student participants. To facilitate this investigation, questions were included in the background and post-activity debrief portions of the 1A and 1B interviews. Consistent with King and Kitchener's model, these questions were designed to elicit student *views of knowledge*, and their *concepts of justification*. The breakdown of interview questions to these two constructs is in Table 9 (the full interview questions are available in Appendix A).

Table 9 Summary of pertinent interview questions and their relationship to King and Kitchener's model

Interview Section	**View of Knowledge**	**Concept of Justification**
1A and 1B Background	4. c) iv. During these experiences, was it ever unclear to you what the actual problem was that you were solving? How did you resolve that uncertainty?	4. c) vi. During these experiences, how did you know when you had found the right solution?
	8. d) During your work term, did you face any situations where you didn't know everything you needed to know to solve the problem?	5. f) During these experiences, how did you know when you had found the right solution?
1B Background (4-Stream)	8. e) During your work term, did you face any situations where the problem you were working on had unclear goals or instructions?	8. e) i. What role did your manager/co-workers play in navigating this? Did you ever disagree with him/her? Tell me about it.
1A and 1B Post-activity Debrief	1. At the beginning of the activity, did you feel like there was missing information in the instructions about what you had to deliver?	8. Can you talk more about the different decisions you made during the activity?
	6. Is there more than one solution to this problem?	8. b) How did you know you made the right decision?
	6. a) How did you know you had found the right solution to the problem?	8. c) How would you justify this decision to your boss?
	7. Have you experienced a problem like this before? Did you solve it the same way?	

In addition to these direct questions to students, occasionally their views of knowledge were brought up organically as they worked on the design activity in the verbal protocol section. This was typically as they were researching information online. Where present, these instances will be included in the case descriptions.

As mentioned in section 4.2, concept coding was employed to interpret the student participant data. The concept codes used were "view of knowledge" and "concept of justification". Once the student transcripts were coded in full (i.e. all three sections of the interview), the coded sections of the transcript were compared against King and Kitchener's Reflective Judgment model (1994, pg. 14-16). King and Kitchener's model is not as well operationalized as Anderson and Krathwohl (2001), especially in the context of engineering design, and so protocol coding (as described in sections 4.2.1 and 4.2.3) was not appropriate here. These analyses focussed on comments made on/during information gathering, idea generation, decisions and decision-making processes, justification, evaluation, and response to an expert, to attempt to describe the level of thinking demonstrated by the student participant in relation to King and Kitchener's (1994) model of personal epistemology. Previous research (Rennick, et al., 2019) had some success evaluating personal epistemology in undergraduate students by investigating their decisions in a design project setting, and so a similar approach is employed here. This approach is also supported by Zhu et al. (2019) who found relativistic thinking in undergraduate engineering students manifested in project-based learning environments when they conducted feasibility analyses with multiple possible solutions; and when they combined multiple knowledge sources including advice from experts, and their own knowledge and independent research.

As discussed above, the primary interview sections that were leveraged for the assessment of personal epistemology were the background and post-activity debrief sections of the interviews, however notable behaviours or comments that took place in the design activity were used to triangulate the assessment. Any incidents of contradiction between how the participant acted in the design activity and how they discussed their designing in the debrief were summarized in the case descriptions. In certain situations, differences between actual behaviour and comments in the debrief; or differences in behaviours or comments at different sections of the interview necessitated a less precise assessment of personal epistemology. In these cases, the personal epistemology was presented as a range; an approach that is consistent with King and Kitchener's description of personal epistemological development. As discussed in section 2.2, King and Kitchener described the development stages as flexible; a person can demonstrate different stages depending on the level of support they receive, and the nature of the task.

In addition to the descriptions of a person's views on knowledge, and their concept of justification, King and Kitchener also included illustrative quotes in their presentation of the model to help illustrate the type of thinking demonstrated at each stage of development. Table 10 includes the sample quotes from King and Kitchener for each stage, as well as sample quotes from this thesis to help illustrate the types of thinking at each stage of development. Stage 1, 2, and 7 have been excluded from this table as there were no observed examples of these stages in this thesis.

The personal epistemological development analyses will be presented in Chapter 9 in chronological order (1A interviews first, followed by 1B). Connections to the design process and process quality analyses will also be discussed in Chapter 9.

Table 10 Sample student quotes for each development stage

Stage	Sample quote from King and Kitchener (1994, pg 14-16)	Sample quote from student participants in this thesis – View of knowledge	Sample quote from student participants in this thesis – Concept of justification
3. Pre-reflective thinking	*"When there is evidence that people can give to convince everybody one way or another, then it will be knowledge; until then, it's just a guess"*	*"Don't know I found the right solution to the problem. Not even close. like I'm sure there's. I keep bringing it back to the idea of, if it [the problem] was defined more, I could have had a better solution."*, Patrick, 1B interview	*"umm… I Imagined using it [my device] and like based on like my imagination, it worked in my imagination, so I was like OK, let's let's go with this."*, Chris, 1A interview
4. Quasi-reflective thinking	*"I'd be more inclined to believe evolution if they had proof. It's just like the pyramids: I don't think we'll ever know. Who are you going to ask? No one was there."*	*"I started by like just making up. Like just thinking of parameters that would be umm intuitive like… The components of the jar have to be intact at the end."*, Chris, 1A interview	*"It was nothing like quantitative. It was all pretty qualitative, just what I felt was the best. And kind of like gut instinct."*, Oscar, 1A interview
5. Quasi-reflective thinking	*"People think differently and so they attack the problem differently. Other theories could be as true as my own, but based on different evidence."*	*"I don't. I don't think it's necessarily like a right or wrong type thing. I just think it's more optimal."*, Patrick, 1A interview	*"I find the way this [the design prompt] is phrased; to sound more like a portable device, because it would be a window opener… I think the way this is phrased is more like a portable device. So I'm gonna go with the portable device."*, Michelle, 1B interview
6. Reflective thinking	*"It's very difficult in this life to be sure. There are degrees of sureness. You come to a point at which you are sure enough for a personal stance on the issue."*	*"There's no right solution, but there are many right solutions, and I think it was the best one because it optimized a lot of lot of the umm… criteria"*, MJ, 1A interview	*"I was maximizing simplicity with this example, minimizing costs… And then, you know… maximizing user friendliness. That's why I chose that idea above the other three."*, MJ, 1A interview

4.2.5 Knowledge and Epistemic Climate Coding - ME 100 Course Instructors

Data for the coding of ME 100 teaching activities came from all sections of the instructor interviews (see section 4.1.4 for an overview of the interview, and Appendix B for the full list of questions).

Knowledge coding was completed using the same method as was described in section 4.2.1, except the focus was on what the *instructors taught* as opposed to what the students recollected of the experience.

To capture data on the epistemic climate of ME 100, questions were included in the instructor interviews to capture data relating to elements of Rule and Bendixen's integrative model (2010). This included specific questions around the social dynamics of the course (e.g. What social interactions did students have with their peers during this exercise), the explicit demonstration(s) of instructor epistemology (e.g. At any point in the course, did you conduct design live with students?), and a section of the interview to capture details on course projects where epistemic doubt and epistemic volition may have occurred.

To analyse these data, the instructor interviews were coded using holistic coding (Miles, et al., 2020) in a similar approach as with the application of Crismond and Adams (2011) as described in section 4.2.3. For epistemic climate, a priori codes were generated from Rule and Bendixen's integrative model for personal epistemology development (2010). Rule and Bendixen provided detailed descriptions of the elements of their model, with example applications to teaching environments. The model has not been operationalized for this purpose to the extent that Anderson and Krathwohl's knowledge categories have, and so protocol coding was not appropriate in this case. The unit of analyses was for individual teaching strategies (e.g. a lecture, a project, a course activity, etc.) The codes were:

- Epistemic doubt – to what degree was the activity ill-structured, dynamic, context-specific, and/or could have multiple solutions or solution approaches that could foster epistemic doubt
- Epistemic volition – to what degree were students given ownership in the activity, was the duration of the activity sufficient for students to act with epistemic volition
- Resolution strategies – to what degree were the instructions, assessments, or interactions with the teaching team designed to assist students with resolving epistemic doubt
- Environmental conditions, including peer interactions and demonstration of instructor epistemology – to what degree were students interacting with their peers and the teaching team, were personal epistemologies discussed, presented, or revealed to students

The data relating to knowledge taught in ME 100 will be summarized and analysed in Chapter 7, while the data relating to personal epistemological development and the epistemic climate of ME 100 will be summarized and analysed in Chapter 9.

4.2.6 Inductive Coding

Inductive coding of the entirety of each participant interview occurred concurrently to the deductive coding described in prior sections. As stated in section 4.2, concept coding (Miles, et al., 2020) was the approach used for the inductive coding. As stated by Creswell and Pohl (2018), one issue with using a priori codes – as was done for the bulk of the coding in this thesis – is that having pre-identified codes can limit the analysis to only the constructs identified before analysis started. To counter some of these challenges, and to enable richer descriptions of the cases, inductive coding was also used to identify important aspects of each case. As deductive coding processes progressed, the researcher added inductive codes to describe important phenomena that were observed in one or more cases. These included relevant "individual differences" as identified by Jonassen (and captured in many other models mentioned in this thesis) like motivation and affect, among other observations. The researcher was also looking for participant statements that were either confirmatory or contradictory to the deductive findings, but which were not captured by the deductive codes.

Description of these codes will be included in the summary of each case in the relevant chapter. Presentation of the themes identified by the inductively coded observations will be presented in standalone sections at the end of Chapters 6 and 8 as "Other Observations".

4.2.7 Cross-Case Analysis Methods

To understand patterns across participants, a conceptually clustered matrix was used to highlight the similarities and differences in knowledge between the participants. Conceptually clustered matrices are useful for "at-a-glance summative documentation and analysis" (Miles et al., 2020). For this matrix, the columns were the knowledge categories described in this thesis (viz. factual, conceptual, and procedural knowledge). Further details of this analysis method will be included in section 5.3 prior to its presentation.

To understand patterns in design behaviour across knowledge groups and levels of personal epistemology, and over time, network displays from Miles et al. (2020) were used. According to Miles et al. (2020), network displays are useful for highlighting complex relationships between multiple variables and are effective at analysing longitudinal trends – methodological strengths that are important to this thesis. The network displays will be presented at the end of Chapters 6 and 8 to relate knowledge to informed design behaviours, in sections 9.1.6 and 9.3.6 to relate student epistemologies to informed design behaviours, and in Chapter 10 to summarize changes in design behaviours between the 1A and 1B interviews.

4.3 Researcher Positionality

The researcher responsible for this study was trained in electrical engineering and has worked in the higher education environment in engineering teaching roles for more than a decade. The vast majority of his professional experience has been in the general realm of mechatronics systems (systems which bridge electrical and mechanical engineering disciplines). So, while he has experience working with, and teaching, undergraduate mechanical engineering students in design environments, he does not have explicit training in mechanical engineering design principles. This professional teaching experience at the undergraduate level generally means the researcher's primary investigative lens was as an engineering educator. In addition to experience in the classroom environment, the researcher also has extensive experience in supervising students while on co-operative work terms in a design environment on a university campus.

The researcher's primary identity as an engineering educator no doubt informed the choice of tools used in this thesis. Anderson & Krathwohl (2001), and Crismond & Adams (2012) were both written with educators in mind; and Atman's design timelines have a growing presence as a teaching tool in design education (Atman, 2024). Because of this alignment, the researcher was familiar with all three of these tools prior to the beginning of the research. For personal epistemological development, the researcher had previous familiarity with operationalizing Perry's model in the context of team-based software design (Rennick, et al., 2019). This familiarity was useful as this thesis sought to operationalize King and Kitchener's model. King and Kitchener's model was deemed more appropriate for this thesis as it was designed with ill-structured problems in mind and was developed through interviews with a more diverse set of interviewees. To counter any biases, the researcher has employed a number of techniques:

- Student quotes are used where relevant to ensure their original voice is presented authentically. The quotes are presented with minimal editing to convey pauses and student uncertainty.
- Memos were used throughout the data collection and analysis sections of this thesis to capture raw thoughts of the researcher and to provide documentation to triangulate observations.
- In this thesis, data will be summarized and presented first, followed by the focussed deductive analyses. These deductive analyses were useful to guide the researcher in exploring the case data. Following this, other analysis/presentation methods will be employed to summarize other relevant findings and conduct the cross-case analyses as described in section 4.2.
- The use of case study methodology and the inclusion of detailed descriptions of the cases in this thesis provide rich, thick descriptions of the data for the reader. This detail and context provide transparency to the reader in the analyses of the data in this thesis. The reader of this thesis is strongly encouraged to read the detailed case descriptions in Appendices C through H.
- The researcher had regular discussions with the research supervisor during all stages of this thesis research. These discussions helped refine the research design; and gave an opportunity to discuss coding and categorization during analysis and write-up. In particular, detailed discussions on coding processes and on noteworthy observations were conducted in all stages of data analysis.
- The researcher has met with the ME 100 DCAP course instructor at several points in the analysis and write-up stages of this thesis research to discuss the findings (the EGAD instructor retired shortly after participating in their interview).

The researcher has been involved in ME 100 as part of the teaching team, and as an external advisor to project groups in past offerings of the course. This history provided the researcher with insight into the course structure and assessments, as well as a relationship to the course instructors before this thesis research began; however, the researcher had no connections to the fall 2021 offering of the course and was not known to any of the student participants prior to the study.

4.4 Overview of Thesis Structure

The following chapters include the results from the investigation into knowledge in the 1A interview (Chapter 5), design behaviours in 1A (Chapter 6), student knowledge in the 1B interview (Chapter 7), design behaviours in 1B (Chapter 8), and personal epistemological development from both interviews (Chapter 9). See Figure 8 for a map of how the results sections map to the research questions. Each of these chapters has a consistent format:

- The initial section(s) present the individual case descriptions and within-case analyses.
- A cross-case analysis of the data is presented.
- A summary of the findings from the chapter are presented last.

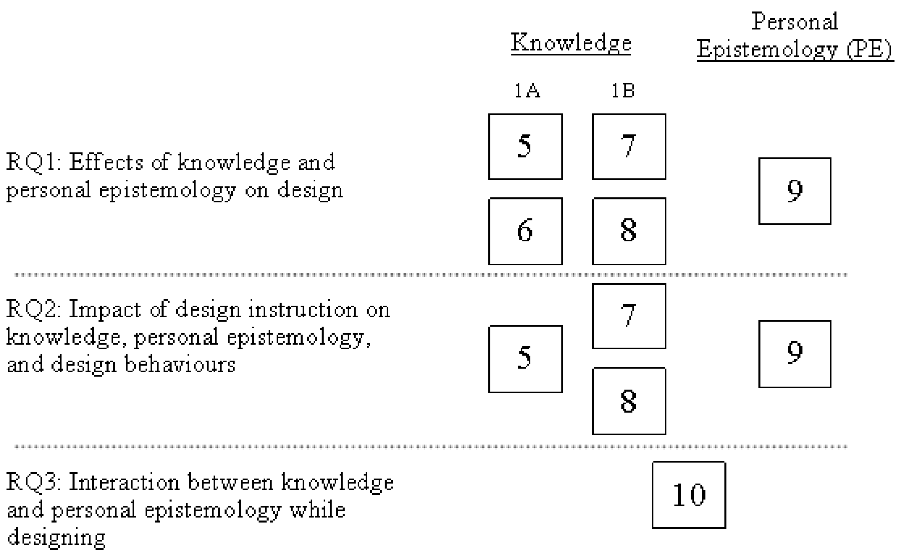


Figure 8 Map of thesis chapters to research questions

In each of chapters 5-9, where the within-case analyses will be presented – Chris' case will be presented in full, followed by the analysis of his data. For MJ, Oscar, Patrick, and Michelle, only a summary of their case description will be included in the main body of the text, with the bulk of the case descriptions included in Appendices C-H. For Jay, Bond, and Jill, their case descriptions and within-case analyses will only appear in the Appendices, for two main reasons: Bond did not return for the 1B interview, limiting the comparisons that can be made over time and to the other participants; and Jay and Jill are similar cases to two other participants (viz. Chris and Michelle, respectively), and so are omitted from the main body of this thesis for readability and concision. This general format aligns with Creswell and Poth's (2018) recommendations to organize the report with readers in mind, and to provide an entry vignette to set the context for the cases (viz. Chris). The reader is encouraged to read the case studies in detail in the Appendices, however they are summarized in the main text of this thesis for clarity and convenience.

5 Results – Student Prior Knowledge

This chapter of results will describe the first section of the 1A interviews where the participants outlined their pre-university experiences. This chapter serves two purposes for this thesis: to introduce the 8 cases in the study and provide a baseline description of their respective experiences and how that relates to their knowledge of mechanical engineering design. Describing this baseline is important to addressing **RQ1** (What effects do knowledge and personal epistemology have on novice designers' design behaviours) and **RQ2** (What impact does one semester of design instruction have on novice designers' knowledge, personal epistemology and design behaviours).

5.1 Student Participants

Recruitment of student participants began on Monday, September 13, 2021 (which was the beginning of the second week of the fall semester) with the help of the ME 100 course instructor. Ultimately, eight students responded to the open invitation to participate – four students from each of 4-stream and 8-stream. The online interviews took place between Sept. 19 and Oct. 9 using Microsoft Teams, at an average interview length of 91 minutes (the shortest was 56 minutes, and the longest was 134). All student participants were assigned a pseudonym during the first interview (they were able to choose their own, if they wished), which will be used throughout this thesis to identify each participant. Two of the participants identified as women, the rest identified as men; and both women were from the 8-stream cohort. A summary of the participants in order of interview date is given in Table 11.

Table 11 Summary of student participants, 1A interviews (Fall 2021)

Participant's pseudonym	Gender	Stream	Date	1A interview length (hrs:mins:secs)
Chris	male	4	Sunday, Sept 19	0:58:30
MJ	male	4	Monday, Sept 20	2:14:00
Jay	male	4	Thursday, Sept 23	0:56:00
Bond	male	8	Saturday, Sept 25	2:07:30
Oscar	male	4	Sunday, Sept 26	1:34:30
Patrick	male	8	Sunday, Sept 26	1:21:30
Jill	female	8	Wed., Sep 29	1:26:00
Michelle*	female	8	Saturday, Oct 9	1:28:30
*Consent was not given for the use of any quotes from the 1A interview				

5.2 Preliminary Analysis of Participant Backgrounds

Each interview started with a short series of questions to capture some demographic data and consent before shifting to a series of questions that sought evidence of prior engineering and/or design experience (full interview script can be found in Appendix A). This opening section of the interview typically lasted between 20 and 45 minutes depending on the participant. All sections of the interview were transcribed automatically using MS Teams (the platform where the interview took place), and were verified (and corrected, where required) before analysis began.

The following sections will summarize each student participant's relevant background details to form a baseline description of each case under study. A more complete presentation of each case can be found in Appendix C. It is important to note that the experiences being described by the participants are all assumed to have happened at a novice level. Generally, these students have not spent sufficient time in any of these experiences to develop expertise. Nonetheless, the participants have taken part in relevant activities in the past that are worth exploring. Following the description of each participant's background will be a discussion and summary of their relevant knowledge. This discussion was constructed using both the knowledge and cognitive process dimensions described by Anderson and Krathwohl (2001). Full details on the analysis can be found in section 4.2.1. Finally, a cross-case analysis was conducted using a conceptually clustered matrix from Miles et. al (2020).

Detailed analyses will only be presented for 5 out of 8 student participants. Jay, Bond, and Jill's detailed descriptions and analyses can be found in Appendix C. Jay and Jill are not covered in detail due to their similarities to other participants (Chris and Michelle, respectively). Bond is not covered in detail for two reasons: his similarities to MJ, and because he did not return for the 1B interview.

5.2.1 Chris

Chris is a male student who completed his high school in Atlantic Canada before attending Waterloo. He didn't feel that anything in his past schooling really prepared him for engineering, but he expressed an interest in motorsports (particularly Formula 1) and cars in general which sparked his interest in mechanical engineering. His part time work during high school was as a lifeguard/swim coach and he mentioned a limited number of extra-curriculars including art lessons and piano. When asked what he is hoping to get out of his degree at Waterloo, he mentioned co-op experience and ultimately a degree are what he was seeking. He had not participated in any organized design activities prior to Waterloo but was able to practice his creativity during painting lessons. The only other relevant experience that Chris mentioned was completing some maintenance work on his personal car, where he turned to YouTube to learn the necessary steps.

Overall, Chris described comparatively few past experiences where he could conceivably have learned the knowledge/skills of engineering design; the background section of his interview lasted about 9 minutes in total. Chris' relevant experiences tended to come from the automotive sector: an interest in Formula 1 racing, as well as do-it-yourself (DIY) vehicle maintenance. These activities could plausibly develop his factual knowledge of common automotive concepts and components, as well as conceptual knowledge of vehicle systems like braking, cooling, and lubrication systems. It is unlikely that these experiences would have developed Chris' procedural knowledge of automotive design, or mechanical engineering in general, though it is possible that some of the online videos he watched included discussions of how various vehicle systems were designed. In general, these experiences would not be expected to extend beyond the "Apply" cognitive process dimension. Table 12 summarizes Chris' relevant knowledge development.

Table 12 Knowledge development from background experiences - Chris

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Limited knowledge of terminology of automotive domain	Interest in professional car racing; online videos and experience with DIY vehicle maintenance	2. Understand – Summarizing
Conceptual	Limited knowledge of components in automotive domain	Online videos and experience with DIY vehicle maintenance	3. Apply – Executing.
Procedural	Limited knowledge of automotive-specific skills, techniques	Online videos on DIY vehicle maintenance	3. Apply – Executing.

5.2.2 MJ

MJ is a male student who completed his high school in western Canada where he completed an International Baccalaureate (IB) program. MJ has held several different jobs including landscaping and working in restaurants. MJ was unsuccessful in his first semester in engineering and so had experienced a first-year undergraduate design course before he was interviewed for this study. His extra-curriculars during high school included a music program, the Shad Valley program in the summer of 2019, and MJ started a small landscape company on his own in the summer of 2020 before coming to Waterloo.

Shad Valley is a month-long STEAM program for grade 10 and 11 students and is offered in many locations across Canada. Shad Canada describes their program as "university level" with entrepreneurship content and access to mentors (Shad Canada, 2019). The program at Shad includes explicit instruction on design and includes a significant team-based project where students apply what they have learned towards solving a "wicked problem". The design process that is taught at Shad is described as a "W-model" with 5 phases:

Define, Ideate, Synthesize, Assess, and Reflect (Moraes, et al., 2019); a process which is described similarly to the better known "double diamond" process model (Design Council, 2019).

MJ also talked about an experience building a zipline in his backyard. This was a course project for his grade 10 IB program, and he described it as an application of physics. MJ talked about getting help from YouTube videos and his father in choosing the materials to construct it, and he completed some sort of modelling of the design that was approved by his mentor at school before construction started.

MJ commented that he was working full time at a restaurant when he joined the university, which sounded like a major contributor to his struggles in fall 2020. MJ's unsuccessful first attempt at university was also in the fall 2020 term during the peak of Covid-19 lockdowns. He had no in-person activity/instruction that term because he was in a different province, likely limiting the effectiveness at promoting higher levels of thinking (see Rennick et al., 2021 for a discussion of this in a similar first year design context). This environment, coupled with the fact that MJ was unsuccessful in advancing past this term makes it challenging to estimate how much knowledge he had retained from the experience; though he commented that he passed every course he took, he just missed the overall term average requirement to advance. MJ was able to discuss the process taught in his first design course and compare it to what was taught at Shad Valley, so it seems that at least some of the procedural knowledge had stayed with him. He also commented that the 3D modelling and sketching taught in fall 2020 was his favorite part of the whole term.

Table 13 Knowledge development from background experiences - MJ

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Knowledge of materials, design tools, and construction tools	Backyard zipline project, online videos, parent/mentor involvement	6. Create – Producing
	Knowledge of terminology and specific details of heavy machinery	Experience/training with landscaping equipment operation and maintenance	2. Explaining
Conceptual	Knowledge of common construction methods	Backyard zipline project, online videos, parent/mentor involvement	6. Create – Producing
	Limited knowledge of component categories in heavy machinery	Experience/training with equipment maintenance while landscaping	3. Apply – Executing.
Procedural	Knowledge of design processes	Shad Valley program, high school course, unsuccessful first term	3. Apply - Implementing
	Knowledge of 3D CAD modelling, sketching	Unsuccessful first term in mechanical engineering program	3. Apply – Implementing
	Knowledge of entrepreneurship and business practices	Started his own landscape company, employment at a professional landscape company, Shad Valley	3. Apply - Implementing

MJ has had explicit instruction and application of multiple design processes from Shad Valley, his high school design technology class, and from his first unsuccessful attempt at 1A at university. From his description, the expectations seemed to be that he would implement the processes as taught, so he does not appear to have any experience differentiating or evaluating processes to determine which one would be more appropriate; the cognitive process dimension seems to be limited to the Apply level, though MJ certainly has the most design process training of any of the participants. MJ's experience at Shad Valley, where entrepreneurship is an explicit component of the project, and with his own landscape company have also likely imparted procedural knowledge of business practices and designing a product for sale. While this is not overly relevant to engineering in general, it is relevant to the design task that was given to the participants in the interview. Table 13 summarizes MJ's relevant knowledge and experiences.

5.2.3 Oscar

Oscar is a male student who completed his high school at a technical school in Ontario prior to coming to Waterloo. During his high school, Oscar took part in machine shop courses and participated on his school's FIRST Robotics Competition team, in addition to completing a co-op placement during high school in the machine shop of a local hospital. FIRST Robotics is an international robotics competition where teams of high school students design and construct large, remote-controlled (though often with partial automation) robots to compete in a challenge defined by the event organizers (FIRST, 2024). Oscar likes to take on personal design projects in CAD and described himself as a "very very amateur woodworker". He also had a paid summer position in 2019 at an automotive manufacturing company with six other students from his robotics team. Oscar has extensive experience with using CAD tools from a high school tech class and through participation in the Skills Ontario CAD competition (Skills Ontario, 2019).

Overall, Oscar is one of the most experienced participants with design and construction with a strong mix of academic learning, projects of varying complexity, and experience in professional work environments. Oscar has taken multiple courses in machining in high school, has designed and/or constructed multiple robotic systems (both high school projects and in a professional setting), and has several years of experience with CAD software including competing at the Skills Ontario competition. Oscar's professional experience was a combination of an unpaid high school coop placement at a machine shop in a hospital and a paid summer position at an automotive parts supplier. Unlike many of the other participants, these experiences were predominantly in person between 2016 and 2019 (i.e. prior to the Covid-19 pandemic) as Oscar enrolled in a fifth year of high school to explore courses in the humanities prior to starting at university in fall 2021. At these positions he got to experience both design for manufacture at the automotive supplier, and constructing a design based on others' plans at the hospital.

This combination of experiences likely provided Oscar with the most hands-on experience in designing and manufacturing mechanical/robotics systems of any of the participants; but Oscar has not formally been taught design methods/processes in any of these experiences. Oscar described his experience in high school as: “the technical side of CAD-ding [sic], rather than… the design side”. Oscar also commented that his mentors in high school were not able to give technical advice to the robotics team; their primary source of mentorship was from students who took part in the team in the past and who were likely undergraduate students at the time. Oscar’s knowledge of design processes appears to consist solely of what he has learned by doing design with his first formal design instruction happening at university. Table 14 summarizes Oscar’s relevant knowledge and experiences.

Table 14 Knowledge development from background experiences - Oscar

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Limited knowledge of materials, design tools, and construction tools relating to woodworking	Self-driven hobby	2. Understand – Explaining
	Knowledge of materials and components of small and medium-sized robots	High school robotics team, summer employment	6. Create - Producing
Conceptual	Limited knowledge of construction methods in woodworking	Self-driven hobby, instructional videos	2. Understand – Explaining
	Knowledge of robotics systems	High school robotics team, summer employment	6. Create - Producing
Procedural	Knowledge of 3D CAD modelling	High school courses & robotics team, high school competition, summer employment, self-driven exploration	3. Apply – Implementing
	Knowledge of machining and manufacturing processes	High school courses & robotics team, summer employment	4. Analyze – Differentiating
	Knowledge of design processes and design for manufacture	High school robotics team, summer employment	3. Apply – Implementing

5.2.4 Patrick

Patrick is a male student who completed his high school in Ontario a few years before enrolling at Waterloo; Patrick spent a couple of years playing competitive hockey before enrolling in mechanical engineering at Waterloo. Aside from hockey, Patrick had been a hobbyist woodworker for several years and had spent a year working at a custom furniture maker during the pandemic. Patrick also had some experience with 3D printing through his woodworking hobby at home.

Patrick did not have much experience with design prior to attending Waterloo. The first section of Patrick’s interview lasted eight minutes. The only relevant experience Patrick brought up in the interview related to his woodworking hobby and employment. Unfortunately, Patrick did not talk extensively about his work experience at the custom furniture maker, so it is challenging to attempt to summarize the knowledge he may have gained there. Between the descriptions of his hobby woodworking and what he did mention, Patrick has experience modelling custom parts in 3D CAD and turning those into functional prototypes with mixed construction (primarily with wood and 3D printed plastic parts). Through this, Patrick would have experience measuring and modeling existing components, designing pieces which could integrate with existing products, and translating those drawings into physical devices. This experience could conceivable have developed his factual and conceptual knowledge of common construction materials like wood, adhesives (e.g. adhesives like PVA wood glue), fasteners like bolts, screws, and nails, common thermoplastics like ABS and PLA, as well as the factual and conceptual knowledge of the various tools for working with these materials (e.g. saws, hammers, abrasives like sandpaper, etc.).

Patrick also would have developed some ad hoc procedural knowledge for designing custom parts and iterating on their design to integrate them with existing tools in his shop. Patrick talked about one example of this in his hobby: “most of it was designing little parts for like woodworking tools. One of my more proud projects is on one of my tools, there… there's no handle to put your hand on the front side, which when you actually use the tool, that's where you want to put your hand to push down onto it. So, I designed like a… a little handle in Fusion 360 that has to have like a clearance hole for a socket head cap screw and then I had to actually drill into the tool and like thread the hole and stuff, so I had to go through a few iterations with the… with the 3D print there.” It is unclear how much procedural knowledge Patrick obtained through his self-study of woodworking on YouTube and his experiences in the professional woodshop, making it challenging to know whether he had any experience evaluating or creating procedures. Conservatively, it could be inferred that Patrick would have had to analyze the different approaches for producing the products he was creating, select one, and apply it. Table 15 summarizes Patrick’s knowledge and experience.

Table 15 Knowledge development from background experiences - Patrick

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Knowledge of materials, design tools, and construction tools relating to woodworking	Self-driven hobby, YouTube instructional videos, experience in professional wood shop	6. Create – Producing
	Knowledge of materials, design tools, and construction tools relating to 3D printing	Self-driven exploration of hobby, YouTube instructional videos	4. Analyze - differentiating
Conceptual	Knowledge of construction methods in woodworking	Self-driven hobby, YouTube instructional videos, experience in professional wood shop	6. Create - Producing
Procedural	Knowledge of procedures for converting part drawings into final products in woodworking	Self-driven hobby, YouTube instructional videos, experience in professional wood shop	4. Analyze - differentiating

5.2.5 Michelle

Michelle is a female student who completed her high school in Ontario prior to coming to Waterloo. Michelle’s extra-curriculars and hobbies in high school tended to be athletics-related, though she credits her interest in Formula 1 racing as the reason she chose to pursue mechanical engineering. Michelle has participated in several online hackathons before coming to Waterloo, as well as a program called Technovation (Technovation Girls, 2023). Technovation connects high school girls with mentors from the business community to create apps which solve local problems in the community. Technovation ran in-person, over the course of approximately 3 months during the school year (but wasn't affiliated with her high school), and had weekly meetings where mentors provided instruction.

Michelle was the last interviewee for this study and was not interviewed until just before Thanksgiving. As such, she had more of an opportunity to participate in extra-curriculars at Waterloo than the other participants. Michelle mentioned that she had joined the Formula student team (where they construct a small single seat race car for a competition each year), and that she had completed the machine shop orientation training as part of her work with the team. As this interview happened later in the term, Michelle also had an extra week or two of instruction in her first semester design course before the interview. At this point in the term, the main lessons that stood out to her were the technical drawing skills and some design philosophy/process knowledge.

Generally, Michelle's past experiences and training fall into three categories: software engineering knowledge, automotive knowledge, and knowledge from ME 100. Michelle's software design knowledge should be the most advanced of the three; she has participated in several hackathons, plus the Technovation project with mentoring. From the interview, it is not clear how Michelle gained her knowledge of programming; it may have been from a structured course, or it may have been self-driven. In addition to the hackathons and Technovation, Michelle also mentioned that she did some personal coding projects like a discord bot. Michelle described a user-centered design process that was taught to her during Technovation, and which she seems to have applied to her work at the hackathons as well. Overall, Michelle could be expected to have experience creating her own apps/programs (she mentioned HTML and CSS but may have experience with other languages as well), and experience in applying the design process she was taught at Technovation. Her knowledge in the automotive domain seems to be from personal interest. She mentioned an interest in Formula 1 after having read a book written by a Formula 1 designer. Like with Chris, her factual knowledge of the automotive domain is likely limited; but unlike Chris, Michelle did not seem to have any experience with the hands-on vehicle maintenance tasks that could have further developed her understanding. Lastly, her knowledge from her first four to five weeks at Waterloo seems to be an introduction to machining, an introduction to technical drawing and 3D CAD software, and an introduction to mechanical engineering design processes/tools. Given the timing in the term, it is unlikely that Michelle had applied any of this knowledge; her experience prior to the interview likely did not extend past the "Understanding" cognitive processes, with the application of that knowledge happening later in the term. Table 16 summarizes Michelle's knowledge in the domains mentioned in her interview.

Table 16 Knowledge development from background experiences - Michelle

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Knowledge of beginner/intermediate software engineering concepts	Hackathons and Technovation	6. Create - producing
	Limited knowledge of terminology and specific details of automotive domain	Interest in professional car racing	1. Remember
	Limited knowledge of manufacturing concepts	Waterloo student design team; machine shop training	2. Understand - Explaining
Conceptual	Knowledge of beginner/intermediate software engineering principles	Hackathons and Technovation	6. Create - producing
Procedural	Knowledge of human-centered software engineering design process	Technovation	3. Apply - Implementing
	Limited knowledge of manufacturing/machining processes	Waterloo student design team; machine shop training	2. Understand - Explaining
	Limited knowledge of technical drawing and 3D CAD processes	First month of ME 100; Waterloo student design team	3. Apply - Implementing
	Limited knowledge of mechanical engineering design process	First month of ME 100	2. Understand-Explaining

5.3 Cross-Case Analysis

As described in section 4.2.7, a conceptually clustered matrix was used to highlight the similarities and differences between the participants (Table 17, below). For this matrix, the columns were chosen deductively from the knowledge categories described in this chapter (viz. factual, conceptual, and procedural knowledge). For each knowledge domain mentioned by the participants, the relevance of that domain to mechanical engineering design, and relative level of participant experience with that domain were estimated and included for context. To organize the rows, the participants were grouped into one of three categories:

- limited relevant knowledge of mechanical engineering design;
- relevant factual and/or conceptual knowledge but limited procedural knowledge; or
- relevant factual and/or conceptual knowledge and relevant procedural knowledge.

Students in the first knowledge grouping (limited relevant knowledge of mechanical engineering design) had no structured training of any kind. Students in the second knowledge grouping (relevant factual and/or conceptual knowledge but limited procedural knowledge) had taken part in relevant experiences like courses or STEM extra-curriculars/competitions but had not had any structured training in mechanical design processes. These experiences could have taken the form of a high school STEM course, participation in STEM competitions or extra-curricular experiences like hackathons, or professional work of relevance to mechanical engineering. The third knowledge grouping were those students with relevant structured training in design processes, either from high school courses, STEM extra-curriculars, or relevant professional work.

Within each knowledge grouping, the participants are ordered from least to most experienced within the group. This ordering considered both the relevance of the domain mentioned by the participant and their level of experience with it. More details on the coding of level and relevance are provided in section 4.2.1. This matrix can be used by looking across each row to get a summary of each participant's relevant knowledge, or by looking down each column to see how the participants differ in their levels of relevant factual, conceptual, and procedural knowledge.

Overall, the participants all had at least some relevant knowledge from their pre-university experiences. While there is a significant difference in the quantity and relevance of experiences between Chris and Oscar, for example, the increase in experience tends to be small between adjacent rows in Table 17. For example, Chris described the fewest relevant prior experiences; however, there is not a large gap between Chris and the experiences described by Jay – the difference stemmed mostly from Jay's high school course on electronics. Outside of the expected high school experiences and hobbies, the participants bring with them a wide variety of meaningful experiences from STEM competitions (Jill, Michelle, and Oscar) to design-focussed enrichment activities like Shad Valley and FIRST (Bond, MJ, and Oscar), and professional experiences in small-scale manufacturing environments (Oscar, Bond, and Patrick). It is worth noting that the last participant to be interviewed (Michelle) also had the benefit of nearly a month of instruction at university prior to the interview.

Table 17 Conceptually clustered matrix: Participant knowledge domains with relevance and level

		Factual			Conceptual			Procedural		
		Domains	Relevance	Level	Domains	Relevance	Level	Domains	Relevance	Level
Limited relevant knowledge	Chris	Automotive	High	Low	Automotive	High	Low	Automotive	Medium	Low
Relevant factual/ conceptual; limited procedural knowledge	Jay	3D printing Electronics	Medium Low	Low Medium	Electronics	Low	Medium	3D modelling 3D printing Electronics	Medium Medium Low	Low Low Medium
	Jill	Programming Airplanes Crafting	Low High Low	Medium Low Medium	Programming Airplanes Construction	Low High Low	Medium Low Medium	Software design	Low	Medium
	Patrick	Woodworking 3D printing	Low Medium	High Medium	Woodworking	Medium	High	Manufacturing	High	Medium
Relevant procedural knowledge	Michelle	Programming Automotive Manufacturing	Low High High	Medium Low Low	Programming	Low	Medium	Software design Manufacturing 3D modelling Design	Low High High Very High	Medium Low Low Low
	Bond	Woodworking Composites Airplanes	Low Medium High	Medium Medium Low	Woodworking Bicycles	Medium High	Medium Medium	Composites Woodworking Design	Medium Medium Very High	Medium Medium Low
	MJ	Construction	Medium	Medium	Construction	Medium	Medium	Design	Very High	Medium
	Oscar	Woodworking Robotics	Low High	Low High	Woodworking Robotics	Medium High	Low High	3D modelling Manufacturing Design	High High High	High High High

5.4 Summary of Findings

The data presented in this chapter do not directly address the three primary research questions in this thesis, their purpose is to describe the eight cases, orienting the reader to the participants; and describe the context of the cases in preparation for the analyses of the design activities in the subsequent chapter.

The student participants had a range of relevant factual, conceptual, and/or procedural knowledge from their pre-university experiences. These experiences were mostly extra-curricular in nature, though there were some instances of relevant high school courses (e.g. Jay's course on electronics, Jill's programming course). The extra-curricular experiences ranged from self-driven explorations of hobbies (e.g. Chris, Jay, Patrick, Bond, MJ), to technology competitions (e.g. Jill, Michelle, Oscar), and enrichment programs like Shad Valley (Bond, MJ), Technovation (Michelle), or Science Olympiad (Jill). Some of the participants had relevant work experiences, either found on their own (e.g. Patrick and Bond), or as part of their high school (e.g. Oscar). However, the bulk of the experiences were limited in one or more ways:

- The experience did not include much formal design instruction,
- The experience did not include much expert mentorship, and/or
- The experience did not require the students to engage with complex cognitive processes (i.e. the "analyze", "evaluate", and "create" dimensions from Anderson and Krathwohl, 2001)

The exceptions to this seem to be Michelle's experience in Technovation; Bond and MJ's experiences in Shad Valley (though Bond's experience seemed to be negatively impacted by the Covid-19 pandemic); and Oscar, Bond, and Patrick's employment experiences in the hospital machine shop, the bike manufacturing plant, and the custom furniture shop, respectively.

The next chapter will present the analysis of the 1A design activity and will rely on the summaries of knowledge presented in this chapter as well as the ordering of participants presented in Table 17. The data presented in Chapters 5 and 6 contribute to the discussion of **RQ1** and **RQ2**.

6 Results - 1A Design Process Analysis

The middle section of each interview with the student participants was a live design activity where the participants gave a concurrent verbal protocol as they designed a device which enables a user to open a jar single-handed. The analysis of the 1A design activity, and the connections to the participants' prior knowledge will contribute to the discussion of **RQ1** (What effects do knowledge and personal epistemology have on novice designers' design behaviours). The design behaviours demonstrated by the participants in the 1A design activity will help form a baseline to contribute to the discussion of **RQ2** (What impact does one semester of design instruction have on novice designers' knowledge, personal epistemology, and design behaviours). To describe the participants' design behaviours, two approaches were used: design timelines were constructed as a descriptive tool to show the design process employed by the participants (Atman, 2019), and the behaviours will be compared against the informed design behaviours in Crismond and Adams (2012). Collectively, these are both useful tools to describe the contents and quality of the design processes used by the participants. For clarity, this chapter will include a brief summary of the design activity for each participant with the analysis; full details can be found in Appendix D.

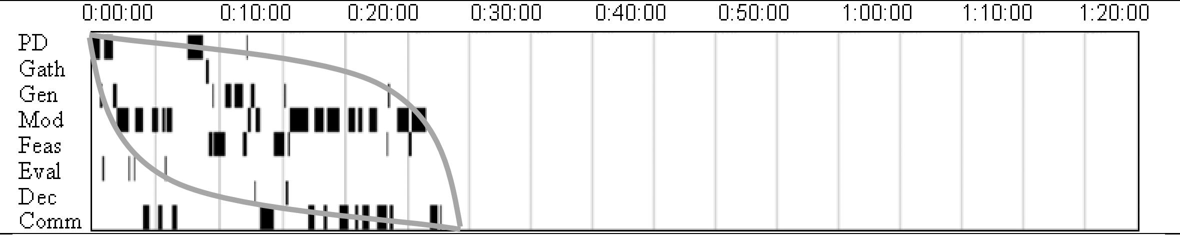
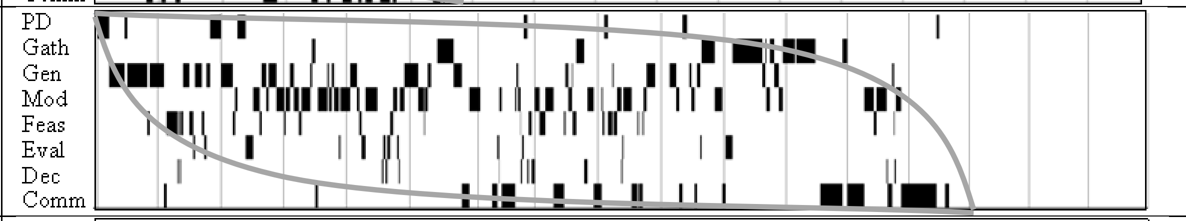
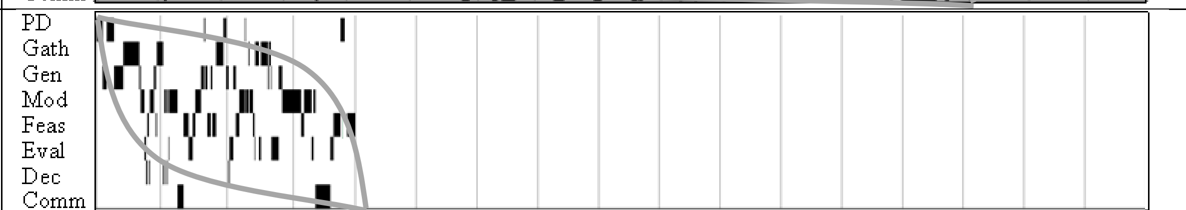
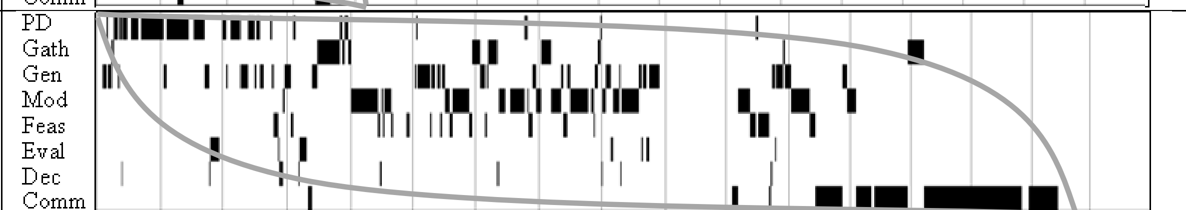
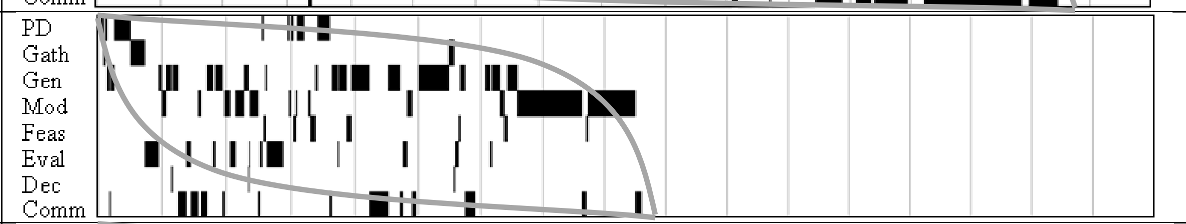
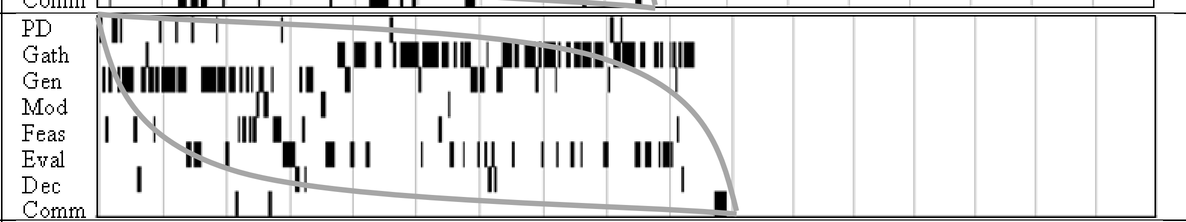
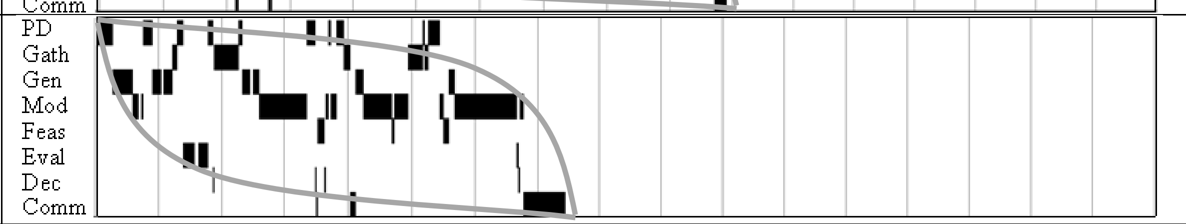
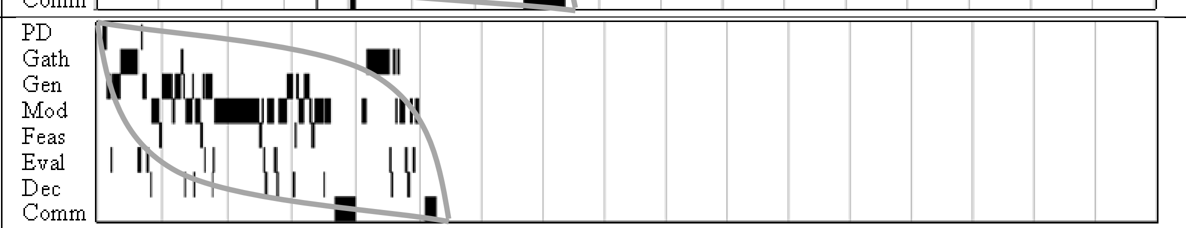
Prior to beginning the live design activity, the students were given two shorter problems to practice thinking aloud as they worked through their solutions. This portion of the protocol matches the process in Ericsson and Simon (1996), including using the same warmup problems (see Appendix A for the full prompts). As stated previously, this verbal protocol was transcribed automatically using MS Teams, and was verified and corrected where needed before analysis began.

6.1 Preliminary Analysis of 1A Design Process

The design timelines for all participants are shown in Table 18 below. To enable a quick visual comparison of the participants' design process behaviour with the behaviour Atman describes for experts (Atman, 2019), the cascade shape has been superimposed over each timeline. Full detail on the analysis method used to generate the timelines is available in section 4.2.2.

As a reminder, these timelines show which step in the design process the participant is thinking about at any given time over the entire duration of the live design exercise. Across all eight participants, the students spent on average 43 minutes and 37 seconds on the design exercise (standard deviation was 19.1; maximum length was 77 minutes, 10 seconds; and minimum length was 20 minutes). During that time, the participants averaged 83 transitions between design process steps, at an average pace of 2.0 transitions per minute (standard deviation was 0.60, maximum was 3.2, and minimum was 1.1). For all but a single participant, the students spent the most time in the modelling step of the design process. Generally, the

Table 18 Design timelines, 1A interviews

Chris	
MJ	
Jay	
Bond	
Oscar	
Patrick	
Jill	
Michelle	

students moved quite quickly through the design process with three completing the task in under a half hour and all but two completing it in under 50 minutes (which is approximately half the allotted time for this exercise). Ignoring Patrick – an outlier who spent 1/3 of his total time gathering information – the students spent little time gathering information (on average, less than 10% of their total design time), even though they were allowed to search on the internet during the design task. These behaviours are similar to what Atman (2019) described for a typical first-year student in a design task.

The following sections present an overview of the design timeline for five participants, followed by a detailed description of the design process with a corresponding annotated timeline. Detailed analyses will only be presented for five out of eight student participants; Jay, Bond, and Jill's detailed descriptions and analyses can be found in Appendix D. Rationale for their removal from the main body are given in section 5.2. A discussion section for each participant follows the presentation of the design process. This discussion highlights connections with prior experience as well as a general assessment of the quality of the process by comparing against Crismond and Adams' Informed Design Teaching and Learning Matrix (2012) (full details on the application of Crismond and Adams is available in section 4.2.3). Where direct quotes are used, they will be presented in the students' voice as much as possible (for example, to help demonstrate the uncertainty in their thinking), though light editing was done to improve readability. As with the results on prior experience, the participants are presented in chronological order by 1A interview date. A cross-case analysis follows the presentation and discussion of the individual cases.

6.1.1 Chris

Chris completed the live design activity in 27 minutes and 30 seconds, the third shortest time of any of the students. During his design process, Chris transitioned between steps 50 times (well below the average number of transitions of 83).

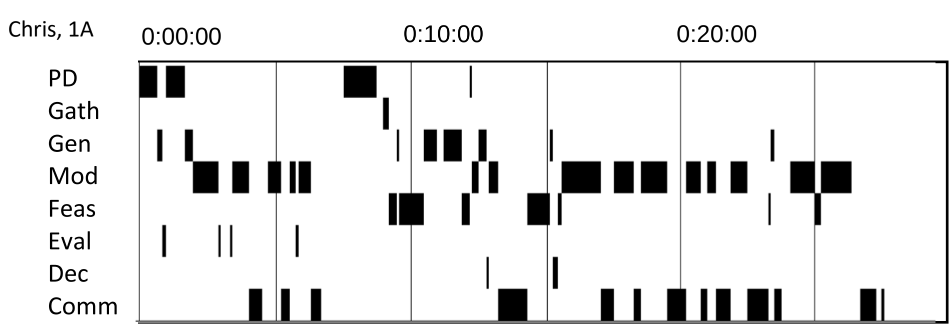


Figure 9 Design timeline of 1A interview with Chris

Chris began his process by making a simplifying assumption: he was considering a small subset of jars – those that are glass with metal lids, like many pickle jars (section a in Figure 10). He also only thought about a single mechanism to remove the lid: prying the lid off by applying force underneath the bottom lip of the lid. Chris spent a bit of time thinking about desirable behaviours in his device (e.g., he didn't want it to destroy the jar), but he conducted no research before jumping into modelling his solution. Early on he realized that a prying action requires something to stabilize the jar while you pry the lid off, and so Chris suggested the user hold the jar in their legs. Quickly, he refined his solution by adding a strap to the prybar which would hold it in place while the user applied force to the handle. His strap solution came to mind by thinking about how some oil filter wrenches are constructed.

At around the 7-minute mark, once his conceptual sketch was finished, he asked a number of clarifying questions (section b in Figure 10). These included clarifying expectations for the quality of the solution he was meant to provide, and then some clarifying questions around the problem and its users. After a short dialog, Chris then spent some time acting out the motions of using his device to understand its operation and any shortcomings (section c in Figure 10). His testing of his idea led him to refine the portion of his device that holds on to the jar (section d in Figure 10) which included both mechanical means to hold the jar, and the idea of the user using their legs to hold the jar. Ultimately, Chris modeled a design that attached his lever device mechanically to the jar through a ratcheting strap but that also required the user to stabilize the jar between their legs. Chris did one more quick check of the process for installing and using his device (section e in Figure 10), where he seemed to be satisfied with its operation. With the remaining time in his design exercise, Chris produced refined drawings of the prototype including detail on how it would be assembled (section f in Figure 10), some overall dimensions, and made some material choices. Figure 10 shows the sections of Chris' design process.

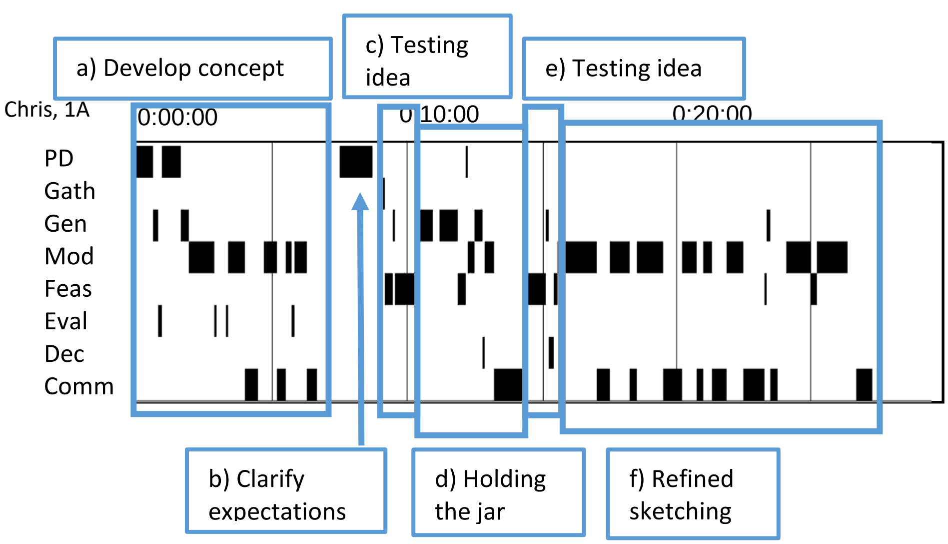


Figure 10 Overview of design process, 1A interview with Chris

Table 19 shows the percentage of his total design time that Chris spent in each design step. Chris spent nearly 40% of his total time modelling, and virtually no time in the gather information, evaluation, or decision steps.

Overall, Chris showed the behaviours of a beginning designer for most of the strategies described by Crismond and Adams:

- He treated the task as simple and well-defined,
- skipped doing any research,
- generated a single idea,
- designed a device that would be challenging to both install and operate with a single hand,
- made decisions without weighing any options, and
- included little iteration or reflection during the process.
- Chris did conduct a worthwhile experiment part way through where he acted out the installation and operation of his device using only one hand, which led to some minor revisions (like including a high friction material where it contacts the jar).

Table 19 Percent of time spent in each design step during 1A interviews, Chris highlighted

Design Phase	**Chris**	MJ	Jay	Bond	Oscar	Patrick	Jill	Michelle
Problem Definition	**10%**	6%	9%	12%	8%	4%	15%	1%
Gather Information	**1%**	13%	17%	8%	4%	33%	12%	14%
Generate Ideas	**8%**	20%	12%	13%	26%	22%	14%	17%
Model	**37%**	23%	26%	19%	29%	2%	38%	38%
Feasibility Analysis	**10%**	7%	16%	6%	4%	5%	3%	3%
Evaluation	**1%**	4%	10%	2%	10%	15%	5%	5%
Decision	**1%**	2%	2%	1%	0.4%	3%	1%	4%
Communication	**23%**	18%	8%	23%	14%	3%	10%	10%
Transitions (mean=83)	**50**	148	64	112	75	112	40	62

Chris demonstrated most of the behaviours we can expect of a beginning designer. This is in line with his relative lack of prior experiences, which are summarized in Table 20.

Table 20 A summary of Chris' prior knowledge, adapted from Table 17

	Factual		**Conceptual**		**Procedural**	
Prior knowledge	**Domains**	**Level**	**Domains**	**Level**	**Domains**	**Level**
Limited relevant knowledge	Automotive	Low	Automotive	Low	Automotive	Low

Chris was able to leverage his knowledge of vehicle maintenance, which helped him come up with a viable design concept for attaching his device to the jar; but such a concrete concept taken from his past may have contributed to his fixation on the single design concept. Chris' solution was also novel in that it was the only device which used a prying action to remove the lid instead of unscrewing the lid from the jar.

Chris also took some time in the middle of his process to act out using his device which led to some small refinements, though these refinements also may have been partly the result of clarifying the requirements for the device with the interviewer. Nonetheless, there was some effort to test the feasibility of his idea. Overall, his design process mostly followed a "waterfall model" where he moved linearly from one step to the next without revisiting earlier steps in the process, and with little iteration.

6.1.2 Protocol Adjustment

After the interview with Chris, the interview protocol for the remaining participants was adjusted to provide some of the answers to questions about the expectations of the solution and design exercise up front. Chris' prompt for the design consisted of just a description of the problem: design a device which can open a jar with one hand, and which could be manufactured by someone else without clarifying any details. For all future interviews, a user was partially specified at the start of the interview by saying the device is required for users with disabilities (a detail that was discussed with Chris when he "clarified expectations" approximately 12 minutes into his design activity). Additionally, the design task was posed as one they could face in one of their co-op placements, including by providing the name of their employer as a way of having them relate to the task better, and to provide another user for them to think about (i.e. the company who would sell the product). The updated instructions more closely align to those given by Atman and Bursic (1998). This similar framing was then also used for the interviews which took place in students' 1B terms (the protocol used in all interviews except Chris' 1A interview is provided in Appendix A).

6.1.3 MJ

MJ completed the design activity in 68 minutes and 18 seconds (1:08:18), one of two participants who took more than an hour (see Figure 11). Over his design time, MJ transitioned between design steps 148 times, for an average of 2.2 transitions per minute, which is above average for this pool of participants.

Figure 11 shows an overview of MJ's design process. In section a, MJ brainstormed concepts for his device, and then in section b, evaluated their feasibility. In section c, MJ thought about the user's needs, which led to more concept brainstorming. In section d, MJ refined the details of some of his concepts that he thought were more feasible, which led to evaluating his options and removing some from consideration in section e. In section f, MJ refined the details for how his device would attach to a kitchen counter, and then in section g he decided on the concept he would implement in full. In section h and I, MJ continued to refine his solution, and in section j, he searched online for mechanisms which could hold a jar steady. In section k, MJ completed a final sketch of his design with instructions for how it would be used.

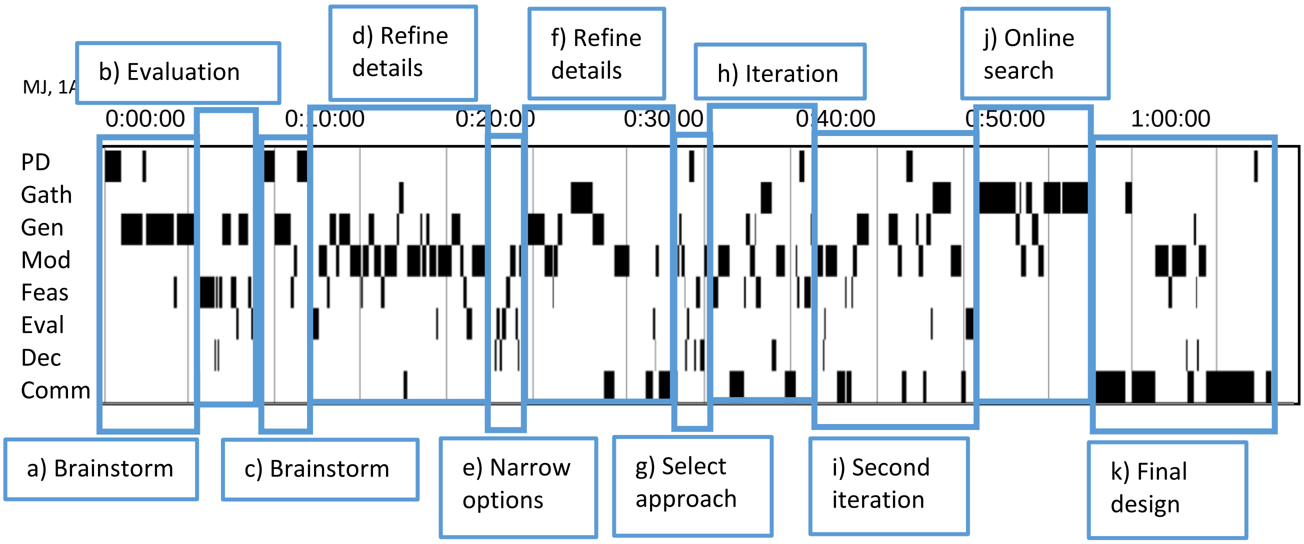


Figure 11 Overview of design process, 1A interview with MJ

Table 21 shows the percentage of total design time that MJ spent in each design step. MJ spent nearly equal amounts of time in idea generation, modelling, and communication. Considering that his total design time was longer than all but one other participant, MJ spent more time in idea generation than any other participant.

Table 21 Percent of time spent in each design step during 1A interviews, MJ highlighted

Design Phase	Chris	**MJ**	Jay	Bond	Oscar	Patrick	Jill	Michelle
Problem Definition	10%	**6%**	9%	12%	8%	4%	15%	1%
Gather Information	1%	**13%**	17%	8%	4%	33%	12%	14%
Generate Ideas	8%	**20%**	12%	13%	26%	22%	14%	17%
Model	37%	**23%**	26%	19%	29%	2%	38%	38%
Feasibility Analysis	10%	**7%**	16%	6%	4%	5%	3%	3%
Evaluation	1%	**4%**	10%	2%	10%	15%	5%	5%
Decision	1%	**2%**	2%	1%	0.4%	3%	1%	4%
Communication	23%	**18%**	8%	23%	14%	3%	10%	10%
Transitions (mean=83)	50	**148**	64	112	75	112	40	62

Examining MJ's design process through the lens of Crismond and Adams' patterns of behaviours, MJ showed a mix of traits of both beginners and informed designers:

- MJ delayed making any decisions on an approach for his solution until nearly 34 minutes into the design activity
- MJ did some searches online for useful information, but they did not turn up much useful information. He did not conduct any search of existing solutions to the problem, though he did search for components which might be useful in his solution
- MJ generated many possible solutions before deciding on an approach, and then generated three solutions to the main sub-problem in his design of how to hold on to jars of different diameters
- MJ was not able to describe his mechanisms in detail, ending with a conceptual sketch of his design that was missing significant detail

- MJ did weigh his options before deciding, but not through any rigorous examination of the alternatives; he tended to remove possibilities based on his instincts of how difficult they would be to implement and use, or if they were outside his experience (e.g. he avoided robotic solutions)
- MJ completed many rapid iterations on solution concepts, refining the problem statement, and generating new concepts in the first half of the design activity, but once his approach was decided on, there was limited iteration and revision of his design
- MJ revisited the problem statement frequently in the first half of the activity, and again at the end of the activity, and did monitor his own thinking to a certain extent, recognizing when he ran out of the knowledge to proceed and trying a different approach.

Arguably MJ had the most prior training in design of any of the participants as he had gone through a university-level course in engineering design and participated in the multi-week Shad Valley program. This was evident in the first half of his design process as he intentionally delayed making any decisions on his approach until a wide variety of alternatives had been investigated, and his understanding of the problem had been refined. MJ also explicitly mentioned using the Shad process while conducting divergent thinking and switched to what was taught in the university level course when convergent thinking. It is interesting that this early focus on being creative did not lead to a particularly creative solution, but no one spent more time understanding the problem and potential solutions than MJ did. It is not clear if he meant to spend nearly 35 minutes on this phase of the design, or if he was perhaps just delaying making any decisions; however, the behaviour is quite different from any of his peers. The general process of generating several creative solutions, refining his understanding of the problem, removing concepts that wouldn't work, before starting the cycle over, seemed to reflect what he was taught in the Shad program, and matches the expert behaviour of using solution conjectures as a way of understanding the problem.

As the process continued, and MJ realized he would need to start filling in technical details, he appeared to lose his confidence; commenting several times that he didn't have the knowledge to do the task in the way that he wanted to do it. This lack of knowledge occasionally caused him to rule out potential solutions – as was the case with the foot-pedal powered concept – because he felt he didn't have the technical knowledge to design that device. This lack of knowledge also appeared in the methods MJ used to evaluate and decide on his concepts, as the criteria he used to make decisions seemed to focus on the simplest design that he felt he could create, if any criteria were mentioned at all. Just before deciding on his final approach, MJ commented that he had a "favorite design", and he was removing the other options without really examining or explaining what made that design his favorite. Overall, MJ was most successful in applying his prior procedural knowledge – especially in the divergent thinking phases of the design activity – compared to his factual and conceptual knowledge of general construction methods.

Table 22 A summary of MJ's prior knowledge, adapted from Table 17

Prior knowledge	**Factual**		**Conceptual**		**Procedural**	
Relevant procedural knowledge	Construction	Medium	Construction	Medium	Design	Medium

The last behaviour of note occurred during MJ's various searches online for information. He struggled repeatedly with finding anything useful, beyond the obvious searches (like the diameter of a standard jar). These searches were unsuccessful for several reasons: in some cases, like when he was searching for the torque required to open a jar, he found a research paper which sought to answer exactly that question. This paper was on his screen for nearly half the design time, but he never read it in any detail to extract useful information from it. In other cases, he didn't have the vocabulary to find the information he was looking for, like when he was trying to figure out how a mechanical iris operated. In many of his online searches, he just didn't seem to take the time to read what he was presented with and think of a next step that might lead to more success. He was always moving on to the next thing, perhaps feeling the constraint of time to complete his detailed design due to the ideation process he undertook at the start.

6.1.4 Oscar

Oscar completed the design activity in 42 minutes and 50 seconds, a minute shorter than the average time for all participants. Oscar transitioned between design steps 75 times while designing, a rate of 1.8 transitions per minute, which is slightly below average for these participants (average number of transitions was 83 at a rate of 2.01/min).

Figure 12 shows an overview of Oscar's design process. In section a, Oscar thought about the problem and wrote some requirements for his design, before looking online for existing devices that solve this problem in section b. During sections c and d, Oscar sketched two concept solutions, and then during section e, he evaluated his concepts which led to refinements to his problem requirements. In section f, Oscar began working on a third concept, starting with a focus on the lid of the jar, before designing the part that would hold the base of the jar in section g. In sections h and i, Oscar refined his third concept, starting with the part that interacts with the lid, and then the part that holds the base of the jar.

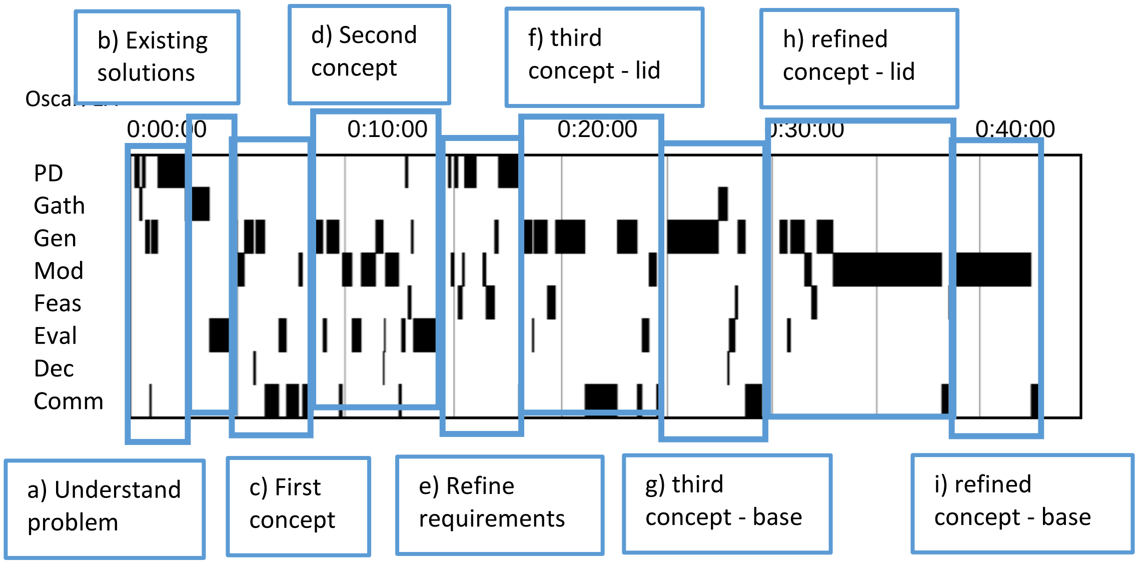


Figure 12 Overview of design process, 1A interview with Oscar

Table 23 shows the breakdown of the time Oscar spent in each design step. Oscar spent the bulk of his time in idea generation and modelling, with about the same amount of time spent in each. Oscar also spent a significant percentage of his overall time in evaluation, only Patrick spent more time in that step. Oscar also spent a significant portion of his time communicating the design to the interviewer throughout his process.

Comparing to the behaviours of a beginning designer described by Crismond and Adams, Oscar showed a mix of mostly beginning designer traits, with some traits of a more informed designer:

- Oscar spent time thinking about the problem, and revisited his requirements after thinking about potential solutions,
- Oscar searched for existing devices, as well as more information on heavy duty suction cups. He also spent some time evaluating the solutions that he saw before going back to his design
- Oscar generated two concepts, iterating and refining on his original concept with each design,
- Oscar's solution would be very challenging to install and use single-handed
- Oscar did not conduct any tests of his concept to evaluate the operation, or compare his proposed solution against his list of requirements
- Oscar made decisions with little evaluation, relying on his intuition
- Oscar iterated on his proposed solution as he learned more about the problem and refined his requirements, but this stopped around the 18-minute mark once he had a concept he liked

Table 23 Percent of time spent in each design step during 1A interviews, Oscar highlighted

Design Phase	Chris	MJ	Jay	Bond	**Oscar**	Patrick	Jill	Michelle
Problem Definition	10%	6%	9%	12%	**8%**	4%	15%	1%
Gather Information	1%	13%	17%	8%	**4%**	33%	12%	14%
Generate Ideas	8%	20%	12%	13%	**26%**	22%	14%	17%
Model	37%	23%	26%	19%	**29%**	2%	38%	38%
Feasibility Analysis	10%	7%	16%	6%	**4%**	5%	3%	3%
Evaluation	1%	4%	10%	2%	**10%**	15%	5%	5%
Decision	1%	2%	2%	1%	**0.4%**	3%	1%	4%
Communication	23%	18%	8%	23%	**14%**	3%	10%	10%
Transitions (mean=83)	50	148	64	112	**75**	112	40	62

Throughout the design activity, Oscar struggled to think out loud when he was processing design details and sketching. This makes it challenging to identify points where he refined his concept, made decisions, and tested its operation; however, given his final design and what he did communicate out loud, it is feasible that he did not conduct any of these types of actions. Overall, his process was conducted in an ad hoc manner, pursuing a single idea and refining it over the course of several iterations. Unfortunately, through these refinements, he lost sight of the original problem and ended up designing a device that could not easily be used single-handed. It is challenging to say how he overlooked this; he seemed to have gotten lost in the requirement of increasing leverage to open a stuck lid at the expense of other requirements.

Table 24 A summary of Bond's prior knowledge, adapted from Table 17

Prior knowledge	**Factual**		**Conceptual**		**Procedural**	
Relevant procedural knowledge	Woodworking Robotics	Low High	Woodworking Robotics	Low High	3D modelling Manufacturing Design	High High High

Throughout his design process, there was a general lack of structure to the process, and a lack of reflection-in-action. Early on, his process appeared more expert-like – he even seemed to be applying methods from ME 100 – as he used solution conjectures and rapid iteration on concepts to refine his design criteria and constraints, but once he found a solution he liked, this behaviour stopped. In general, his factual and conceptual knowledge did not seem to factor into his solution; had he gone with an electrically driven device, perhaps that would have been different. He did seem to be employing procedural knowledge of mechanical design in the early parts of his process.

6.1.5 Patrick

Patrick completed the design activity in 49 minutes and 30 seconds, six minutes longer than the average time, where he transitioned 112 times at a rate of 2.3 transitions per minute, which was a much higher than average number of transitions (the average was 83).

Figure 13 shows an overview of Patrick's design process. Patrick began by developing an initial concept of a device akin to an artificial arm in section a. In section b, Patrick thought about some other concepts and refined his device requirements, and then in section c, Patrick developed a concept which used a strap clamp from woodworking to hold the jar. In section d, he considered different types and sizes of jars, and thought about the materials he would use, which led to an online search of existing clamp designs in section e. In section f, Patrick researched injection molding online as a potential manufacturing method for his solution. In section g, Patrick looked at existing clamp designs again, before looking at alternative manufacturing methods in section h.

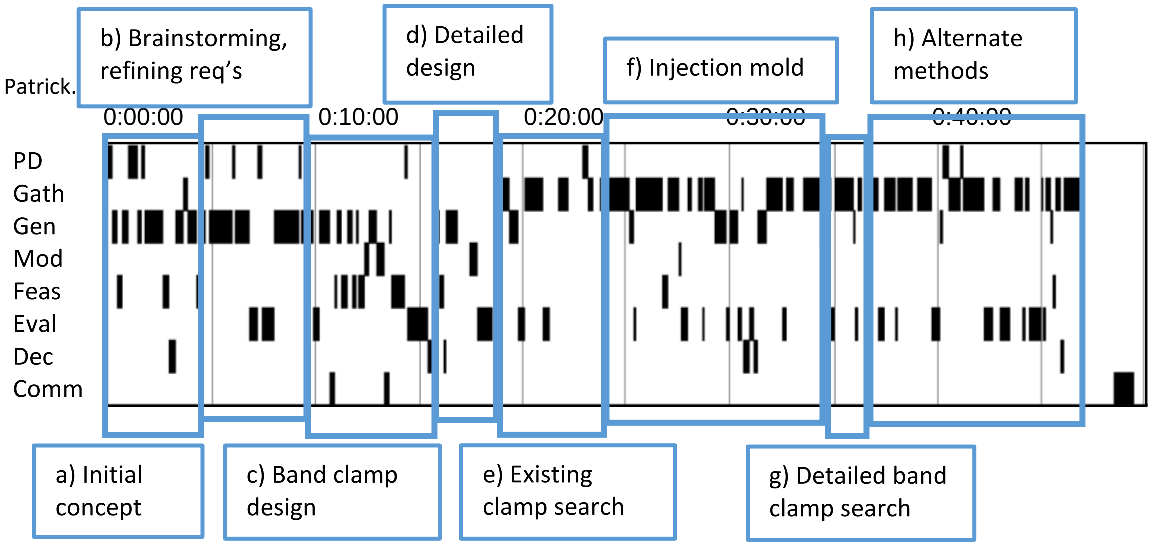


Figure 13 Overview of design process, 1A interview with Patrick

Table 25 shows the percentage of time that Patrick spent in each step of the design process. Patrick behaved quite differently from the others: he spent very little time in modelling (2%) and spent a full third of his time gathering information online. Patrick also spent more time in evaluation than the others.

Table 25 Percent of time spent in each design step during 1A interviews, Patrick highlighted

Design Phase	Chris	MJ	Jay	Bond	Oscar	**Patrick**	Jill	Michelle
Problem Definition	10%	6%	9%	12%	8%	**4%**	15%	1%
Gather Information	1%	13%	17%	8%	4%	**33%**	12%	14%
Generate Ideas	8%	20%	12%	13%	26%	**22%**	14%	17%
Model	37%	23%	26%	19%	29%	**2%**	38%	38%
Feasibility Analysis	10%	7%	16%	6%	4%	**5%**	3%	3%
Evaluation	1%	4%	10%	2%	10%	**15%**	5%	5%
Decision	1%	2%	2%	1%	0.4%	**3%**	1%	4%
Communication	23%	18%	8%	23%	14%	**3%**	10%	10%
Transitions (mean=83)	50	148	64	112	75	**112**	40	62

Thinking about the behaviours of a beginning designer described by Crismond and Adams, Patrick showed a mix of mostly beginning designer traits, with some traits of a more informed designer:

- Patrick did not spend much time thinking about the problem, he broke it into two sub-problems (holding the jar, and then holding the device steady) and jumped into possible solutions quickly, though he would occasionally mention features that his design should have to be successful
- In the 25 minutes where Patrick did most of the work on his design concept, he sought out no new information on the problem outside of the provided problem statement,
- Patrick generated two concepts, merging them into a solution that resembled his original idea,

- Patrick's solution might be a little awkward to use and install, but would solve the problem
- Patrick did reflect on how a user with a single hand would interact with his device, acting out its operation at multiple points in the first 25 minutes,
- Patrick iterated on a few details of his proposed solution as he learned more about manufacturing methods, but the final solution was very similar to his initial idea,
- Patrick spent no time in modelling, produced no sketches, and made few explicit decisions
- Patrick made decisions with little evaluation, relying on his intuition

Table 26 A summary of Patrick's prior knowledge, adapted from Table 17

Prior knowledge	**Factual**		**Conceptual**		**Procedural**	
Relevant factual/ conceptual; limited procedural knowledge	Woodworking 3D printing	High Medium	Woodworking	High	Manufacturing	Medium

Overall, Patrick's design process was only 25 minutes long before the search for manufacturing methods. The combination of struggling to find useful information online, plus how he reacted to the experimental setting seemed to cause him to get lost in his internet searching on manufacturing when there were many details left undecided in his design that were more in his control (e.g., dimensions, shape of his solution, etc.). At various points in the interview, he seemed to be reacting to the setting of the posed problem being for a fictional company and didn't want to commit to any solid details without a dialog with others in the company. It's possible that his time working in a production woodworking shop, and the relationship he had with his employer/supervisor(s) had undermined his perceived agency to make design decisions. It was also curious that Patrick did not write anything down or sketch his solution while working on the problem even though he was given explicit permission before the activity to grab a pencil and paper. This was not the way the other participants reacted to the design activity and runs counter to the heavy emphasis on sketching that is presented in EGAD (this will be discussed more in Chapter 7). Patrick's factual and conceptual knowledge from woodworking were used in his solution. Woodworking clamps were a common source of inspiration for the clamping operations that his device required.

6.1.6 Michelle

Michelle's interview was the final one conducted in the fall term, taking place on Oct. 9, just before reading week. This meant that Michelle had received approximately four weeks of instruction in her 1A courses. Michelle completed the design activity in 26 minutes and 20 seconds, nearly 20 minutes less than the average time of 43:37; making her the second fastest to finish of all the participants. Michelle transitioned between design steps 62 times at a rate of 2.35 transitions per minute. This is a lower number of transitions than the average of 83.

Figure 14 shows an overview of Michelle's design process. Michelle began by brainstorming how to hold the jar lid, and how to power her device in section a, before looking at existing solutions in section b. In section c, Michelle acted out opening a jar as she developed her initial concept, and then refined the details of that concept in section d. In section e, Michelle gave an overview of her design to the interviewer, before stating that she was finished. After a short pause, Michelle realized she had not designed the electrical system, which she refined in section f. In section g, Michelle researched typical jars, which led to refinements to her solution in section h.

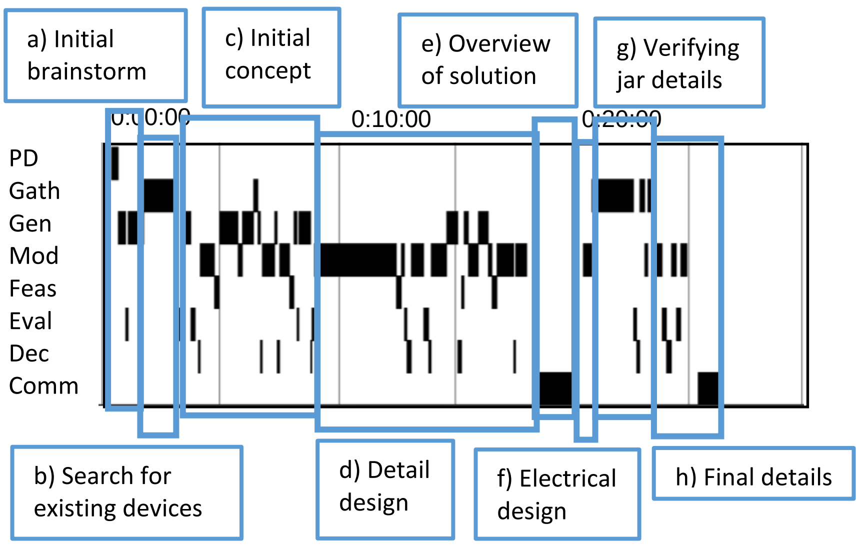


Figure 14 Overview of design process, 1A interview with Michelle

Table 27 shows the percentage of time that Michelle spent in each of the design steps. Michelle spent virtually no time in problem definition, with the majority of time her time spent in the modelling step.

Table 27 Percent of time spent in each design step during 1A interviews, Michelle highlighted

Design Phase	Chris	MJ	Jay	Bond	Oscar	Patrick	Jill	**Michelle**
Problem Definition	10%	6%	9%	12%	8%	4%	15%	**1%**
Gather Information	1%	13%	17%	8%	4%	33%	12%	**14%**
Generate Ideas	8%	20%	12%	13%	26%	22%	14%	**17%**
Model	37%	23%	26%	19%	29%	2%	38%	**38%**
Feasibility Analysis	10%	7%	16%	6%	4%	5%	3%	**3%**
Evaluation	1%	4%	10%	2%	10%	15%	5%	**5%**
Decision	1%	2%	2%	1%	0.4%	3%	1%	**4%**
Communication	23%	18%	8%	23%	14%	3%	10%	**10%**
Transitions (mean=83)	50	148	64	112	75	112	40	**52**

Comparing to the behaviours of a beginning designer described by Crismond and Adams, Michelle generally showed the behaviours of a beginning designer:

- Michelle spent little time understanding device requirements, though mentioned a few items her design should have early in the process (e.g. should adjust to different lids)
- Michelle researched prior solutions, but then seemed to fixate on one existing solution,
- Michelle generated one or two ideas for each of the major components of her device,
- Michelle conducted no tests of her proposed ideas,
- Michelle designed a device that was missing a lot of detail, especially in the electro-mechanical aspects of the design, but which would be fully operable by someone with only one hand,
- Michelle made decisions with little evaluation, relying on her intuition, and
- Michelle developed a single design concept, based on an existing solution, and included no iteration or reflection while designing

Somewhat akin to Jill who proposed a solution and used that to better understand the problem, Michelle also used the solution she had in mind to understand the requirements of the design problem. Unlike Jill, Michelle was always pushing to move forward with her original design, just using these reflective moments to make decisions about her in progress solution. Michelle never paused to think about the general requirements of the device, she dealt with each requirement as she ran into them in her modelling of the solution. This process meant she never evaluated and decided between plausible alternatives, though her process did require her to brainstorm solutions to problems she encountered along the way.

Though Michelle had received approximately four weeks of instruction in ME 100 before the interview, she did not seem to use any knowledge gained from the course. A student at that point in the term would have learned about design criteria and constraints, which are a typical way of thinking about the requirements of a design solution, and yet Michelle did not mention either term during her designing. Like Jill, Michelle also designed an electro-mechanical device, though Michelle's was slightly simpler overall. As with Jill, Michelle's solution was not very complete, especially with the electrical components. Overall, Michelle's solution lacked significant details in the mechanical construction, but the concept of the device was there. The electrical design was missing all but the most superficial details. In general, her past factual and conceptual knowledge did not prove useful to the design that she pursued in this activity.

Table 28 A summary of Michelle's prior knowledge, adapted from Table 17

Prior knowledge	**Factual**		**Conceptual**		**Procedural**	
Relevant procedural knowledge	Programming Automotive Manufacturing	Medium Low Low	Programming	Medium	Software design Manufacturing 3D modelling Design	Medium Low Low Low

Looking at Michelle's past design experiences, most of her prior designing was done in software hackathon settings. These types of environments can be good for learning; however, they prioritize speed above all else. Throughout Michelle's design activity, it seemed as though she was in a "sprint": she was always moving forwards, never pausing to think or reflect. She spent no time framing the problem, instead jumping immediately to see what others had done and then iterating on an existing design. In many ways, her solution seemed "hacked" together from an existing solution with some improvements, much the way software tends to be put together in hackathons (Gama, 2017)(Long, 2014). An alternative possibility is that Michelle saw in an early online search that there was already an existing solution, and so didn't see a need to exert much effort in creating a new one of her own.

6.2 Cross-Case Analysis

Analysis of design processes and the impact of their pre-university experiences will be presented through two lenses: analysis of the design timeline features of experts (Atman, 2019), and analysis using Crismond and Adams' informed design teaching and learning matrix (Crismond & Adams, 2012).

6.2.1 Analysis of Design Timelines

As described in section 1.1.2, in summarizing two decades worth of studies using design timelines, Atman (2019) found that compared to first year students, graduating students were more likely to engage in decision and communication steps, engage in more transitions across steps, gather information on a broader set of issues, and create higher quality products; and experts were more likely to spend more time solving the process, delay modeling until later in the process, gather more information on a broader set of issues, and consider a larger and broader set of objects as they were designing.

Table 29 Design timeline(s) for student(s) with limited relevant knowledge

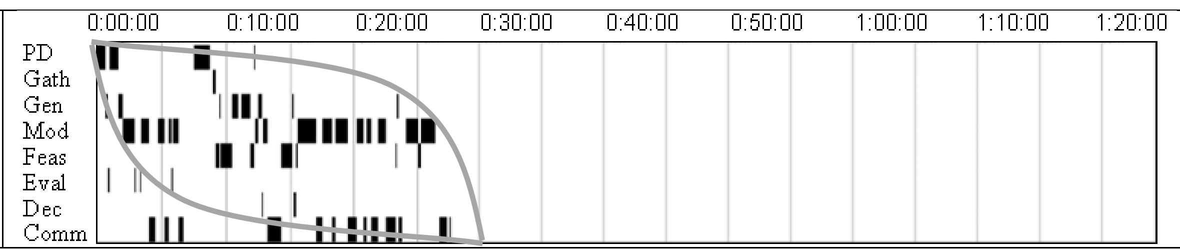
Chris 27.5 mins 50 transitions (1.8/min)	

Table 29 shows the design timeline and relevant details of the participant design process for the student with limited relevant pre-University knowledge (viz. Chris). Chris seemed to match Atman's description of beginner/first-year designers. Chris completed the design in the third shortest time overall, with a below average number of transitions during his design time (the average was 83 transitions), and 60% of his overall time was spent in modelling and communication. Chris was able to leverage his prior knowledge of automotive maintenance in generating his design concept. It is worth reiterating that Chris was the first student interviewed (and so had the least amount of university-level instruction), and the problem statement was changed after Chris' interview as described in section 6.2.2.

Table 30 shows the design timelines and relevant details of the participant design processes for the students with relevant pre-University factual/conceptual knowledge and limited procedural knowledge. This group of participants were highly variable in their behaviour; these 3 students represented many of the witnessed extremes in behaviour. Jay was the quickest to finish the design activity and had a higher rate of transitions in design process steps than any other participant (though Jay had a below average total number of transitions), Jill had fewest number of transitions in her design process of any participant, and Patrick spent more time gathering information (both as a percentage of his overall design time, and in absolute terms) than anyone else. In this group, Jay's process most resembled Atman's cascade shape, but each of the participants deviated from that pattern in one way or another. Jay and Jill did not communicate much decision-making, Jill also did not conduct much evaluation during the design activity, while Patrick got lost in information gathering in the second half and conducted no modelling. As with Chris, this group appears to behave similarly to the first-year students described by Atman: they didn't engage in much decision-making or communication, they did not collect information on a broad set of issues, did not consider a broad set of options, and did not spend much time solving the problem. This group of participants each leveraged their prior knowledge at various points in their design process, but they seemed to move through the design activity with a mostly ad hoc process, addressing issues in the design as they noticed them.

Table 30 Design timeline(s) for student(s) with relevant factual/conceptual knowledge and limited procedural knowledge

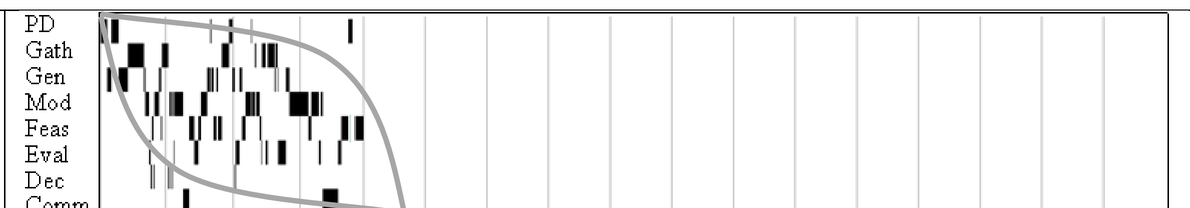
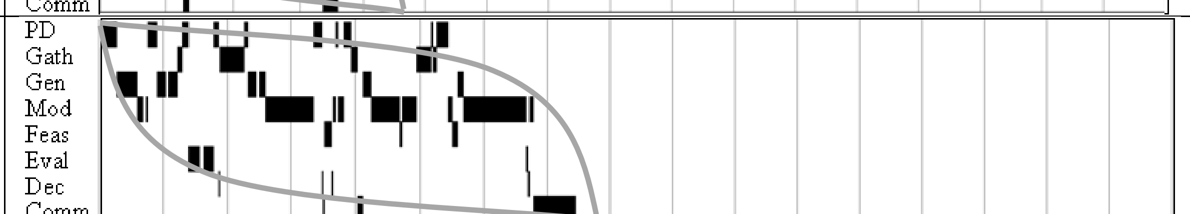
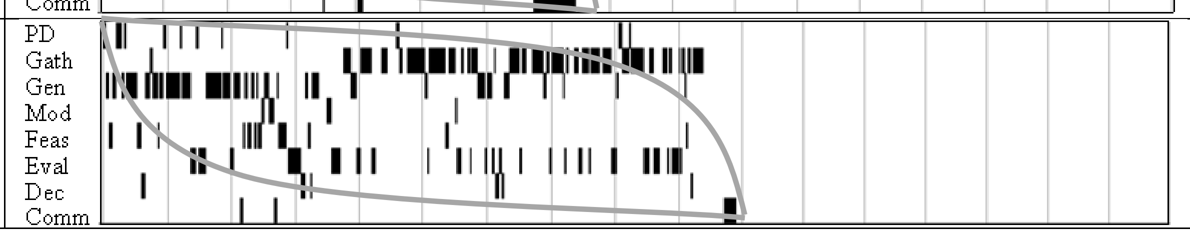
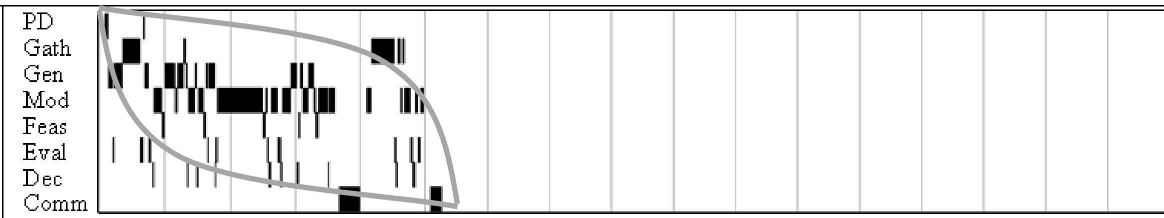
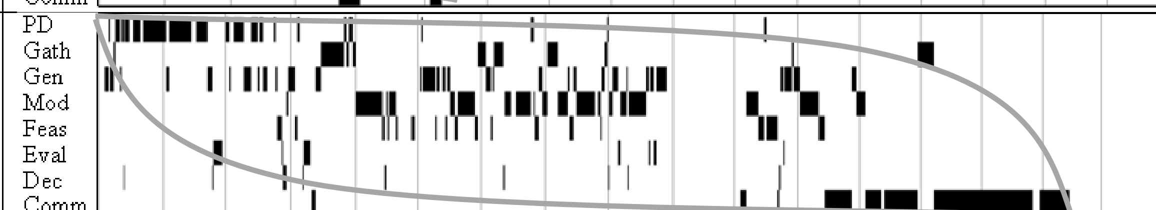
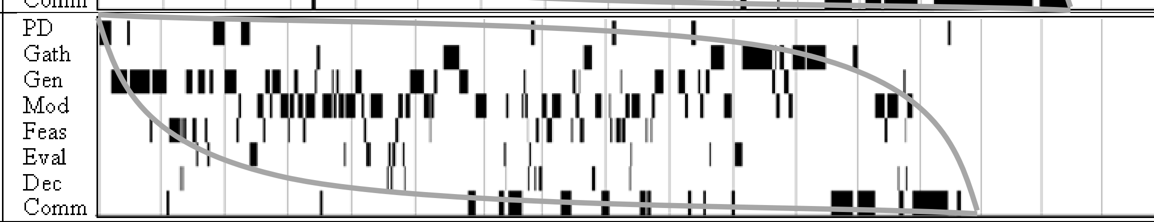
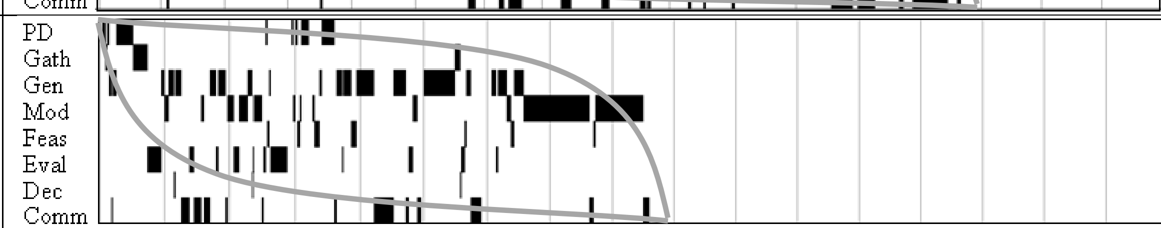
Jay 20 mins 64 transitions (3.2/min)	
Jill 37.3 mins 40 transitions (1.1/min)	
Patrick 49.5 mins 112 transitions (2.3/min)	

Table 31 shows the design timelines and summary details for the students with relevant pre-University procedural knowledge. This group of participants represented the most experienced participants, and this was reflected in their design (though Oscar exhibits many of the same issues as Jill with his limited testing of ideas and decision-making), though there was still variability in their behaviours when comparing against Atman's description of graduating students or experts. This group of students spent more time working on the design problem than the other participants and spent more time in the combination of decision-making and communication (though skewed towards communication). MJ and Bond had higher numbers of transitions than the 1A average. Bond's and MJ's design process timelines most resemble the cascade shape that is common to design experts.

Table 31 Design timeline(s) for student(s) with relevant procedural knowledge

<table>
<tr><td>Michelle
26.3 mins
62
transitions
(2.4/min)</td><td>
</td></tr>
<tr><td>Bond
77 mins
112
transitions
(1.45/min)</td><td>
</td></tr>
<tr><td>MJ
68.3 mins
148
transitions
(2.2/min)</td><td>
</td></tr>
<tr><td>Oscar
43 mins
75
transitions
(1.8/min)</td><td>
</td></tr>
</table>

Michelle's design process appears the least expert-like of this group; with most of her time spent modelling (38% of her total time). The bulk of Michelle's procedural knowledge of design came from hackathon-style software design events. It is conceivable that the design process she developed in these events (which tend to move quickly due to time constraints, and where there is little opportunity for expert feedback to correct bad habits) was not helpful in this setting. For MJ, the first 50 or so minutes of his design activity were going well until he hit the limits of his mechanical design knowledge. It was at this point where he got a little lost in an online search of useful components for his device. It is conceivable that fatigue was also becoming an issue at this point as he had already been talking for an hour and 40 minutes at that point – time longer than all but one of the other interviews in their entirety. While Bond commented that he didn't take the Shad Valley program very seriously (as it was online), it is possible that this earlier experience primed him for the teaching in ME 100. For example, it was Bond who most used the information he had been taught in their 1A design course during his design activity (viz. thinking about criteria and constraints while designing), and it is his process which most resembles the cascade shape common to design experts.

6.2.2 Analysis of Informed Design Behaviours

To quickly summarize the intersections of knowledge and design behaviours, Figure 15 below shows a visual map of informed design behaviours for each participant in the 1A design activity. As explained in section 4.2.3, to construct this map, one explicit behaviour was identified for each "design strategy" in the Informed Design Teaching and Learning Matrix in Crismond and Adams (2012).

From this map, a few observations can be made:

- Chris with limited relevant knowledge demonstrated 2 behaviours; the participants with relevant factual knowledge but limited procedural knowledge demonstrated 4, 6, and 5; and the participants with relevant procedural knowledge demonstrated 5, 7, 7, and 6.
- The behaviours from least common to most common are weighed benefits/trade-offs before making decisions (1); created detailed drawings (3); researched problem space (4); generated range of concepts, and revisited design goals (6); researched solution space, and stated explicit design goals (7); and evaluated solution against design goals (8)
- Participants with relevant procedural knowledge represent 3 out of 4 of the participants who researched the problem space, 2 out 3 of the participants who created detailed drawings, and the only participant to weigh benefits/trade-offs before making a decision

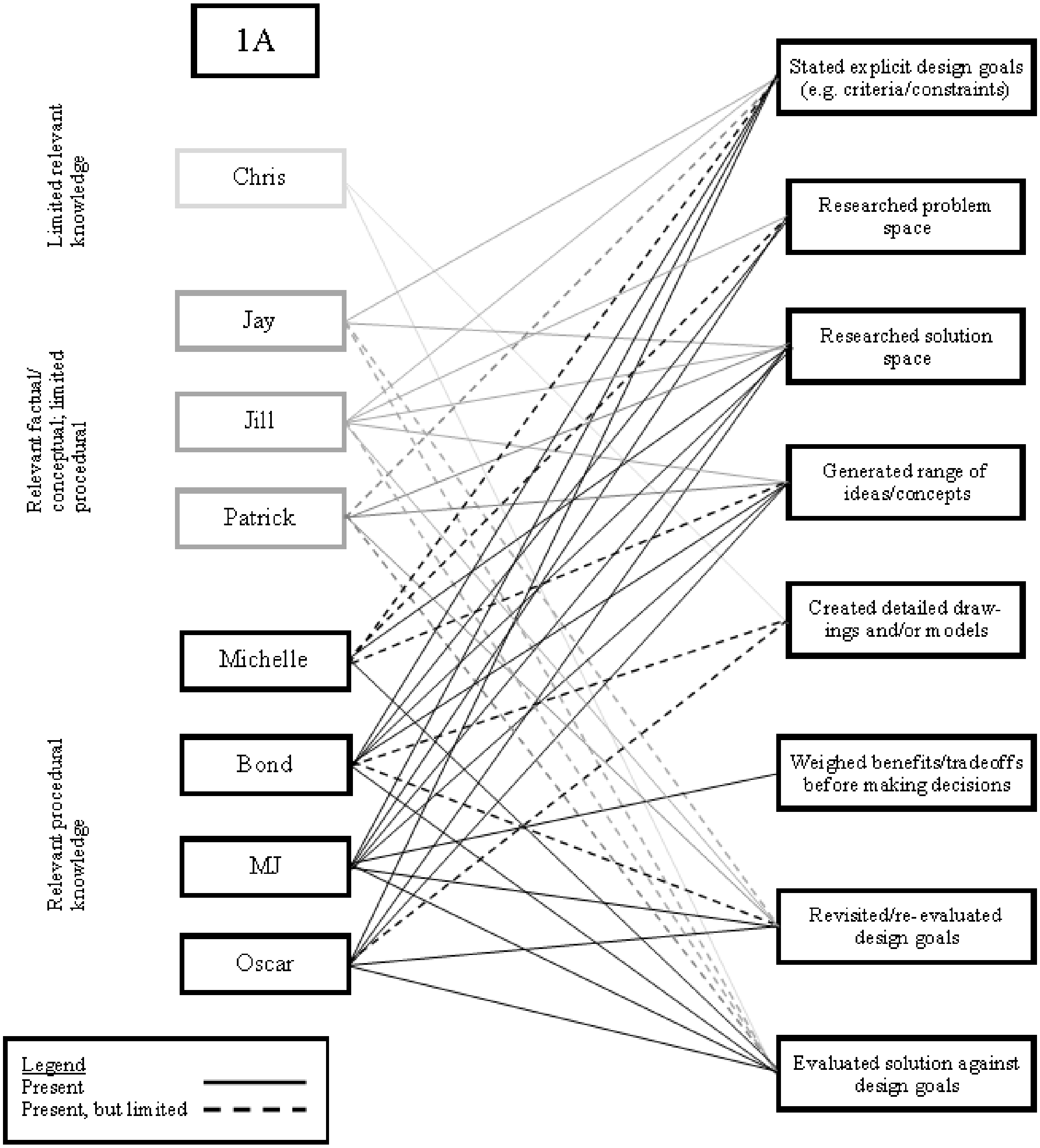


Figure 15 Map of student performance against indicators of informed design behaviour, 1A interview

6.2.3 Other Observations

There were several common traits during their design exercise, including ineffective information gathering – when it happened at all. Some of the participants did not search for any additional information (Chris, for example), while others struggled to identify useful information outside of the original problem statement. In other online searches, many participants seemed to struggle with the correct vocabulary for components, or sub-assemblies leading to challenges in finding useful information online. For example, MJ found relevant research but seemed unable to extract much useful information. MJ also had seemed to have trouble finding useful sub-components (in his case for a tightening mechanism to hold the jar), even commenting on his lack of knowledge which led to a difficulty in assessing the value of information he found online. Others also had trouble with online searches including Jay (who ended up falling back on his knowledge of vehicle maintenance instead of conducting a detailed search), Bond (who wanted to see how a scissor lift mechanism worked), and notably Patrick who spent a full third of his design time gathering information. Jill also struggled with finding an answer online to the simple question of which way to turn the lid to unscrew it. This was frequently an issue with vocabulary (i.e. the declarative knowledge of mechanisms and components), but it also could have been a result of some of the participants rushing through the process and not wanting to slow down to conduct a thorough search online. Interestingly, only two students used the opportunity to search for existing solutions (Michelle and Oscar), both of whom fall in the more experienced group of participants, though it is possible that the others felt this search wouldn't be permitted and so neither asked permission, nor conducted the search.

The participants also did not produce a design with sufficient detail where it would be ready to manufacture, even though they were instructed to do so. This manifested in different ways but was frequently evident whenever two different components were joined together in their designs. Participants rarely, if ever, described how these components would be fastened together (e.g. through adhesives like glue, or fasteners like screws). This was particularly evident whenever electrical or electro-mechanical elements entered their designs; the participants did not provide details on the electrical components (like motors) that their design would require, and frequently did not incorporate spaces into their designs where the electrical components could be housed, or where wires could be routed, for example.

The participants also did not use any analysis methods to assist in making decisions beyond simple calculations like the relationship between the diameter of a circle and its' circumference. This is not surprising, as analysis methods relating to, for example, materials selection, component strength, forces, or stresses and strains form the bulk of the engineering science they will learn during their later courses. In the absence of these more rigorous methods, decisions were made quickly, with little explanation of the thinking that led to the decision. Interestingly, few of the participants showed any activation of the knowledge (of any kind) or skills they had been taught in ME 100. The format of this course will be expanded on in the next section, however, all participants had at least two weeks of instruction in the course prior to the interview and yet little of the concepts or language taught in the course showed up. One notable exception to this was Bond who brought up what he had been taught multiple times during the interview. It is interesting to note that Bond was only the fourth student interviewed (on Sept. 25) and so had less instruction from the course before the design activity; at the other extreme, Michelle had an additional 2 weeks of instruction before her interview (on Oct. 9).

Many of the participants directly leveraged their prior knowledge from pre-university activities that they described in the opening part of the interview. It is possible that the discussion of their prior experiences activated this knowledge, and so it was front of mind as they entered the design activity. It is also possible that they were leveraging the only relevant knowledge they had access to, whether it was directly relevant or not. For example, Chris used his knowledge of automotive repair when using an oil filter wrench as a reference design; and Patrick used his knowledge of woodworking clamps as a reference in his solution.

Oscar and Jill used solution concepts to understand the requirements of the problem in a way that resembled the concept of expert "solution conjecturing" described by Dorst and Cross (2001). Using solutions early in the process to understand the problem is not taught in ME 100; in fact, they are instructed to not think about solutions until later in the process, once they understand the problem (Bond even mentioned this explicit in his interview). It is not clear where they picked this up, or if it is an intuitive approach based on experience. This approach, especially in a novice, could also be viewed less charitably as a "trial and error" approach to designing, and there was some evidence of that with Jill. However, with both participants, they spent relatively little effort on the conjecture and followed it with re-evaluating their understanding of the problem as opposed to finding a different solution or iterating.

Lastly, many participants would stop vocalizing their thoughts when working on detailed designs of their concepts. Oscar and Jill were notable examples, though this happened to some degree with everyone. This may have been a result of cognitive overload as they thought through the specifics of their concept. This no doubt hindered the ability to accurately analyse their design processes; it is likely that transitions between phases were lost, especially as it relates to the evaluation and decision-making steps in the process.

6.3 Summary of Findings

The data presented in this chapter were used to explore the effects of knowledge on novice design behaviour, and to set a baseline of design performance to enable a comparison to the 1B design activity. A summary of the data as they relate to **RQ1** will be presented next.

6.3.1 Effects of Knowledge on Novice Designers' Design Behaviours

Summarizing the student design processes through the lens of Atman's design timelines (Atman, 2019), the following observations can be made:

- There was variation in the behaviours exhibited by the student participants, even within the groupings based on pre-university knowledge
- The group with relevant procedural knowledge generally spent more time solving the problem, spent more time generating ideas, and spent more time in decision-making/communication steps
    a. Michelle was an outlier here; she completed the task very quickly and spent less time in decision-making/communication compared to the others in the group

Summarizing the design processes using Crismond and Adams (2012), leads to the following observations:

- Students with more pre-university experience demonstrated more informed design behaviours
    a. students with relevant procedural knowledge demonstrated the most (two students with seven behaviours) and the student with the least pre-university experience demonstrated the fewest (two behaviours)
- Very few students weighed benefits/trade-offs (one student), created detailed drawings (three students), or researched the problem space (four students); while virtually all the participants researched the solution space (seven students), stated design goals (seven students), and evaluated the solution against their design goals (eight students)
- Students with relevant procedural knowledge were more likely to research the problem space, create detailed drawings, and weigh benefits/trade-offs before making a decision

Participants with limited relevant factual knowledge were still able to leverage what they had. However, this knowledge may have been more accessible in memory as the design activity immediately followed a detailed discussion of their past experiences. This also may have led to design fixation or a lack of divergent thinking. For example, Chris and Jay used the analogy of an oil filter wrench, Patrick thought about wood working clamps, and Bond referenced bike parts in his solution. Where the participants didn't have the required knowledge and turned to the internet for answers, it was generally not very helpful. For some students, this led to significant time spent on information searches with little impact on their designs. This was most notable in Patrick's process but was common to many of the participants.

Generally, the participants were weakest in the conceptual knowledge category. This is perhaps one of the causes for their generally weaker detailed designs. Only three students attempted to create detailed drawings or models of their solutions (Chris, Bond, and Oscar), with Chris conveying the most detail about his solution. The bulk of the solutions that were presented in the 1A design activities can more accurately be described as conceptual sketches, and not detailed designs. For example, materials, dimensions, and fastening/joining methods were generally omitted. Understanding how materials come together into mechanical assemblies will be taught at various points in the mechanical engineering curriculum and may be learned experientially through work term experiences as students solve problems in industrial environments. When the design drifted into a multi-disciplinary solution space (typically by bringing in electro-mechanical elements), the quality of the solution was low. Many of the participants were conscious of their lack of knowledge of the electrical domain and so intentionally made purely mechanical devices, though Jill and Michelle each included electromechanical elements in their solutions. As commented earlier, these elements in both solutions were missing significant detail where Jill and Michelle simply didn't have the knowledge base to specify. For the other participants, their recognition of their lack of knowledge (or their lack of confidence) of the electrical domain may have steered them away from potentially fruitful solution concepts, narrowing the diversity of solutions considered.

For procedural knowledge, Michelle, Bond, and MJ had prior training in design processes and Oscar had a large pool of prior experience to draw on; and this additional experience manifested itself in their design processes. Bond demonstrated more informed designer behaviours than most of his peers. He seemed able to integrate what he was taught in ME 100 and put it to use. He was the only student to write "criteria and constraints" for the problem in 1A, though Oscar may also have been using that way of thinking about the problem (and didn't vocalize it). This is especially interesting as Bond and Oscar were the two middle interviews; three students were interviewed before them, and three after them. There was also some evidence of functional breakdown to break the problem into smaller pieces; Bond, Jay, and Patrick all did this to some extent in their design activity. It is not clear if this was something they learned from ME 100 (Bond alluded to this when discussing the coffee maker dissection in ME 100) or if it just came naturally.

Thinking about other engineering processes, very little evaluation happened in any interview. The participants obviously haven't yet been taught the engineering science required for some of the calculations they wanted to complete, and they haven't been taught methods for assisting them with evaluation and decision making. Bond even talked about this explicitly during the design activity when trying to calculate the clamping force and torque required to grab a jar lid and unscrew it. Some of the participants were self-aware enough to recognize this is work that should be done and that they were just not capable of it in the moment (e.g. Patrick discussed this a couple of times during the design activity).

Lastly, some other observations based on the 1A interviews. Many of the participants struggled with the cognitive complexity of the think aloud process. This was most evident with Bond, Oscar, and especially with Jill. Interestingly, Bond and Oscar were two of the most experienced participants. Few participants made explicit assumptions when they dealt with missing information, though Oscar and Jill were notable exceptions here. The others made a snap judgement and moved on; or avoided the situation any way they could (perhaps by pivoting their solution to a new direction or ignoring the missing information).

7 Results – Teaching and Learning in 1A Term

This chapter will describe the experiences the participants had prior to their 1B term. This includes the experiences the participants had in their first university design course (ME 100), experiences from extra-curricular activities like student design teams, and for the 4-Stream students, this could also include a co-operative work term. This chapter, in combination with the results in Chapter 8, will explore **RQ1** further (what effects do knowledge have on novice designers' design behaviours). This chapter will also explore **RQ2** both directly and in combination with the results in Chapter 8 (what impact does one semester of design instruction have on novice designers' knowledge, personal epistemology, and design behaviours). The chapter will start with a detailed overview of ME 100 and then transition to the results from the 1B student participant interviews.

7.1 University Design Instruction – ME 100

The first semester of Mechanical Engineering at Waterloo includes a single design course, with two components: the Design, Communication, and Professionalism (DCAP) portion, and the Engineering Graphics and Design (EGAD) portion. A copy of the course syllabus for ME 100 in fall 2021 was obtained; it described the course objectives as:

- be able to apply engineering methods (including engineering design processes) to problems they encounter in classes and on work terms
- be able to communicate effectively, in written, oral, and graphical form
- appreciate the roles and responsibilities of the profession of (mechanical) engineers in Canada, and know what their place in it is/if they are in the right program
- be more confident in their technical, non-technical, and hands-on skills
- be prepared to participate in the co-op system and to write a work term report

From this high-level description, the course is seeking to develop students' knowledge of engineering methods, including design processes in tandem with other relevant engineering skills like communication and professionalism. This would seem to be a mix of factual, conceptual, and procedural knowledge. The course is also seeking to develop student confidence in their engineering skills as well as develop their sense of identity in the program. These could perhaps be considered an element of metacognitive knowledge (viz. self-knowledge). While metacognitive knowledge isn't strictly relevant to this study, improvements to metacognitive knowledge may manifest in higher motivation to work on design problems, or enhanced design behaviours in the 1B interviews.

The course syllabus described the general structure of the course: EGAD is taught in a three-hour lab session each week and represents 40% of the overall course grade, while DCAP is taught in three hours of lecture, plus three hours of tutorial weekly for 12 weeks and represents 60% of the overall course grade. Assessments in DCAP consisted of a term design project, shorter duration design challenges with reflections, and a number of other required learning modules (e.g. WHMIS training, co-op preparation, etc.) Assessments in EGAD consisted of weekly assignments and two quizzes during the term. EGAD and DCAP are taught by different instructors, and both were interviewed separately at the end of the 1A term to capture details on how design was taught in ME 100. Both interviews took place on December 9, 2021, and were each approximately an hour long. The following two sections will summarize these instructor interviews.

7.1.1 Design Knowledge and Skills Instruction – DCAP

The Design Communication and Professionalism portion of ME 100 (DCAP) included three hours of lecture, plus a three-hour tutorial weekly. This tutorial was used to house the various active learning activities that occur throughout the course. Prior to fall 2021, the instructor for DCAP had co-taught the course with experienced instructors four times and was teaching the course for the first time as the sole instructor in the term under study. For the fall 2021 term, due to the Covid-19 pandemic, lectures were conducted online, while active pedagogies were conducted in person. Due to campus Covid-19 restrictions, only half the class could participate in these in-person sessions at any one time. ME 100 is a large course – weighted 0.75 credits (or 1.5 times a regular course at Waterloo) – that, in the words of the course instructor, needs to take high school students, help them adjust to university life, and get them ready for their first work terms and the mechanical engineering curriculum that follows. This is the only engineering course in this semester (the other courses are chemistry, physics, and math courses), and the instructor emphasized the inclusion of activities that “feel” like engineering so the students could start forming their identity in the program. The course covered design from initial ideation through designing, building, and testing physical prototypes. The course also had an emphasis on communication, including written and oral communication, plus graphical communication (described in the following section on EGAD). Teaching materials consisted of presentation slides and activity/assignment descriptions, and no textbook.

Lecture content on design started in the first week of the term, introducing students to multiple engineering design process models, before describing one in more detail: the PRIMED design process. PRIMED stands for *Project/problem/product, Research, Ideate, Make, Evaluate, Decide* and maps very closely to the process used in constructing the design timelines used in this thesis (feasibility analysis and communication are the only two steps missing from the process used in the timelines, otherwise they are the same). Multiple forms of problem formulation were presented to students, but the language of “constraints” (or features that your design *must have* to solve the problem), and “criteria” (or features that your design *could have* to distinguish one design from another) were used through most of the teaching and learning activities in the course. Decision matrices were also introduced to students in lecture as one way to formalize the design making processes that are required when designing but were not heavily emphasized in the later design projects.

Case studies, and project-based learning were used throughout the course to reinforce the instruction of design and provide practice opportunities for students. In the second week of the term, students took apart a household coffee maker; in the third week, the students constructed and tested paper rockets and were presented with a case study of a pill crusher in lecture. There was also a project that runs throughout most of the term where students design and build toys for a toy-making industry partner. This larger project was mostly confined to the second half of the term; however, it was introduced to students in the first week, and students began what the instructor called "blue sky ideation" early in the term to come up with possible ideas. These projects and case studies had a mix of pen and paper conceptual designing (pill crusher), and design that ended in a prototype that is demonstrated/tested (the rocket and toy project). The coffee maker dissection introduced the parts and pieces that make up a common household item.

The bulk of the work on the toy project occurred over five weeks in the second half of the course. This phase of the project began with students submitting a written proposal on their idea. The teaching team provided feedback to the students on their project idea and gave suggestions on how to start prototyping their solution. Two weeks later, the students presented their prototypes to the teaching team to receive more feedback on their design and to ensure they were making progress. The students were then given three weeks to finish off their toy prototypes before they were presented at a class-wide symposium. Throughout the project, the instructor repeatedly reminded students that they were being assessed on the execution and communication of their design process, and not on the outcome of their prototyping. The instructor assessed the project in this way to encourage intelligent risk-taking/creativity, and to remove some of the stress that requiring a working prototype could bring to the project.

7.1.2 Design Knowledge and Skills Instruction – EGAD

The Engineering Graphics and Design portion of the course (EGAD) was taught in a single three-hour lab section each week. The instructor for the EGAD portion of ME 100 has taught the course for many years, and previously worked as a designer in industry. For the fall 2021 term, due to the Covid-19 pandemic, students alternated between in-person and online on a weekly basis (i.e. half the class came in person one week and then were online the following week when the other half of the class came in person). The core learning in EGAD was technical communication: hand sketching, AutoCAD, and SolidWorks were all taught. Design instruction was presented throughout but was secondary to the instruction on communication and their associated tools. The term started with instruction on hand sketching and drafting techniques, and AutoCAD instruction; and approximately halfway through, the instruction transitioned to 3D modelling with SolidWorks. This course is perceived by students and the instructors as very important for the work-readiness of the students, with the EGAD instructor saying that this is the course that teaches students the skills they will use everyday at work. As half of these students were scheduled to have a co-op work term immediately following this academic semester, this instruction was timely. The course contains regular active, hands-on learning experiences throughout the term. The instructor had created a custom set of course notes, several hundred pages long, that the students were required to purchase and use during the term. Throughout the course the instructor was both teaching the necessary skills of CAD and modelling, and sharing bits of wisdom he collected over his years of experience designing products in industry. Many of these tips and tricks were included in the appendices of the course notes; a resource he provided to the students to add to the usefulness of the notes once they were finished with his course.

The general structure of the course instruction each week included an introduction to a particular skill or set of skills in drawing and/or CAD, time for the students to practice these skills with the teaching team present, and a follow-up assignment that was due at the end of the week where student skills were assessed, and feedback was given. Wherever possible, the examples were taken from real devices from either the industrial world, or from engineering projects on campus. Most of the weeks had well defined tasks with demonstration of the skill, followed by written instructions, as the students practiced what they were just taught, though there were four design challenges assigned to students that were more open.

In the first week, students were presented with a problem given by a fictitious work term boss: design a back rest for a canoe seat. As students thought about the problem, the instructor intentionally slowed down the process, getting the students to think about “good” traits for this design. For example, the backrest had to fold, or be removable, it had to be easy to assemble, it had to be waterproof, etc. This problem provided the instructor an opportunity to talk about criteria and constraints as they related to a design problem before these topics were introduced formally in the course. The final task for students was to quickly sketch potential solutions on the back of a paper plate (simulating an environment where you need to communicate a design idea quickly and no paper is present).

A couple weeks after the canoe seat problem, students were presented with a partially completed design for a hoist that was installed on a mezzanine to lift pallets up to the second floor. The students were instructed to analyse the movement of the device in AutoCAD. For example, to ensure that the lifting mechanism won’t impact the floor of the mezzanine. For the weekly assignment, the students were instructed to correct design flaws that were identified through the geometric analysis in CAD. Before transitioning to SolidWorks, the students also designed a snowflake in AutoCAD that was laser cut out of cardboard. The students were given space to be creative, and once they received their laser cut snowflake, could inspect it for design oversights or issues introduced when their design was made into a real item.

Near the end of term, the weekly rhythm changed when a multi-week, individual design project was introduced to the students: the design of a 3D-printed cell phone stand. In the first week after it was assigned, the students came up with a list of functions that their solution “must have”. In the second week of the project, they produced at least two alternative hand sketches of possible designs. These sketches were then verified by the teaching team to ensure that the ideas were realistic and manufacturable. In the third week of the project, the students selected a design and construct it in SolidWorks. This allowed the students to include a model of their phone and calculate a centre of gravity for their design; providing them an opportunity to analyse whether it would be stable, or tip over, when in use. The design was again verified by the teaching team to ensure it could be manufactured and it met the requirements of the design. The cell phone stand was then 3D printed, and the students verified their design with their actual phone in the final week. They were instructed to verify if the phone could stand up, as well as investigate other possible functions like whether the phone could be plugged into a charger while on the stand.

One other activity in the term was the keychain activity. This was introduced in EGAD, and then completed during class time in DCAP. In this activity, students spent about an hour in a machine shop to complete the manufacture of a small keychain. Students drilled and tapped holes, drilled countersinks and counterbores for different types of screws, and then assembled the keychain as a small keepsake. Through this activity, students used a drill press and hand tools and were exposed to a number of different fastener types. In EGAD, the instructor also walked students through the process of machining the keychain components – steps that were completed for students by professionals in the engineering machine shop on campus.

7.1.3 Preliminary Analysis – Knowledge Instruction in ME 100

Table 32 summarizes the expected knowledge development from the combined teaching activities of both parts of ME 100. This table was constructed to reflect an expected minimum amount of knowledge developed in any student in the course. Additional detail on this method of analysis is presented in section 4.2 of this thesis. Depending on what each student did during the various activities in the term, they may have developed some of this knowledge beyond what is described here. For example, the DCAP instructor mentioned a group who constructed a toy which generated jets of water. That group would have developed knowledge of electric pumps, control electronics, and tubing, valves, etc. beyond what this table lists. The subsequent sections on each participant will include these more individualized knowledge types.

Table 32 Expected knowledge development from teaching activities in ME 100

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Limited knowledge of common materials and manufacturing methods	Keychain activity, coffee maker dissection, toy project	6. Create – Producing
	Limited knowledge of materials, design tools, and construction tools relating to 3D printing	Phone stand project	3. Apply - Executing
	Knowledge of common crafting materials and tools	Paper rocket activity, toy project	6. Create – Producing
Conceptual	Limited knowledge of common components of mechanical design	ME 100 instruction, ME 100 projects	6. Create – Producing
	Limited knowledge of common construction methods	Keychain activity, paper rocket activity, toy project	6. Create – Producing
Procedural	Knowledge of design processes	ME 100 instruction, ME 100 projects	3. Apply - Implementing
	Limited knowledge of ideation methods	ME 100 instruction, toy project	3. Apply - Implementing
	Limited knowledge of structured decision-making methods	ME 100 DCAP instruction, toy project	3. Apply - Implementing
	Knowledge of 2D/3D CAD modelling, sketching	ME 100 EGAD instruction, hoist design assignment, phone stand project	6. Create – Producing
	Knowledge of manufacturing with 3D printers, laser cutters	Phone stand project, snowflake assignment	3. Apply - Implementing
	Limited knowledge of machining and manufacturing processes	Keychain activity, EGAD instruction, toy project	3. Apply - Executing

On several occasions during their respective interviews, both instructors mentioned material that had been removed from their course, or material that had been taught in the past, but is no longer part of the course. The EGAD instructor spoke about the high perceived workload for students both in his course, and in the term more broadly, and so pieces of the course were removed. The DCAP instructor spoke of past activities that are no longer part of the course as well, but it was less clear if those were replaced by something else, or if the course just had fewer teaching and learning activities. Fall 2021 was an exceptional term during the Covid-19 pandemic; the limitations on in-person teaching activities that term, plus the capabilities of first year students in a hybrid learning environment, likely played a role in the capacity of students to meaningfully engage in all the activities that had been part of this course in the past. Nonetheless, it seems as though less was taught in ME 100 in fall 2021 than in prior in-person years.

In both EGAD and DCAP, there were limited opportunities where the instructors demonstrated their thinking as they solved a design problem with the class. In EGAD, this occurred in a limited way when the hoist design case study was introduced, in the context of the original design of the device which the students then needed to investigate and improve. In DCAP, this occurred with the pill crusher case study, and to a lesser extent when discussing the design of the paper rocket launching mechanism (which is a compressed air tank and valve). There were, however, repeated opportunity for students to apply what they were taught both shortly after learning the content, and again in later projects. There were also instructor demonstrations of the skills being taught through short case studies in both DCAP and EGAD.

Assignments and projects in EGAD were completed individually throughout the term; while in DCAP, many of the activities and projects were team-based. In many ways, this is a nice balance of individual and group assessment, which required students to practice applying their communication skills in EGAD as individuals, while still having meaningful team-based work in DCAP. In both parts of the course there was limited knowledge sharing among students; students were instead mostly directed to the instructors and course TAs to acquire new knowledge; though there were a few exceptions to this. In EGAD, the teaching team would occasionally show examples of strong assignments to the class, and in DCAP, the students were given the opportunity to see the work of their peers at the toy project symposium. This will have larger implications on the epistemic climate of the course and the epistemological development of these students, but that discussion will be saved for a later section.

There was a consistent philosophy in both EGAD and DCAP to have limited summative assessment of the quality of the designs produced by students, and to instead assess their application of the design process, and/or their communication skills (written, oral, or graphical). There were opportunities during the term where students were given formative feedback on the execution of their projects, most notably in the toy project in DCAP and the cell phone stand project in EGAD. Much of this feedback seemed to be focussed on the manufacturability of the respective projects, however, teaching team concerns with safety (in particular), and likely other shortcomings of the designs, were also discussed.

During the cell phone stand project in EGAD, the instructor repeatedly informed students to not look at reference solutions online so that they could bring a fresh perspective to the problem that wasn't coloured by prior existing devices: "I deliberately say on the cell phone stand, stay off the web, and I repeat that because as soon as you see that it just shrinks your thinking down". This project occurred long after the 1A design interviews for this thesis, but if this perspective was repeated in earlier parts of the course as well, this could help explain why some of the students were reluctant to look up existing solutions online. There is a tension here in that stopping them from looking online does not match real design practice; a designer needs to have a strong understanding of prior art both to avoid real, or perceived, theft of intellectual property, or to simply avoid reinventing the wheel. There is also tension between the two sides of the course as the DCAP instructor explicitly told students if a portion of their toy project can be purchased and repurposed, that is preferable over trying to redesign an already existing component/device. An alternative explanation for why students did not seek out existing devices in the 1A interview is that they did not think they had permission to do so and were reluctant to ask the interviewer for permission.

7.2 Preliminary Analysis of 1A Student Experiences

The second interview with each participant took place in the first three weeks of their second academic semester in first year (the 1B term). Seven of the original eight participants returned for the second interview (Bond did not respond to the request for the follow up interview). For the 8-stream students – Jill, Michelle, and Patrick, these interviews took place on January 15, 2022 (Michelle), January 16 (Jill), and January 19 (Patrick). For the 4-stream students – Chris, Jay, MJ, and Oscar – these interviews took place after their first work term on May 7, 2022 (Chris), May 8 (Jay and Oscar), and May 9 (MJ). Table 33 summarizes the dates and lengths of each of the 1B interviews.

Table 33 Summary of student participants, 1B interviews (Winter/Spring 2022)

Participant's pseudonym	Gender	Stream	Date	1B interview length (hrs:mins:secs)
Michelle	female	8	Saturday, Jan. 15	2:13:55
Jill	female	8	Sunday, Jan. 16	2:18:54
Patrick	male	8	Wed., Jan. 19	2:15:46
Bond	male	8	Did not respond	----
Chris	male	4	Saturday, May 7	1:21:39
Jay	male	4	Sunday, May 8	1:00:00
Oscar	male	4	Sunday, May 8	1:41:53
MJ	male	4	Monday, May 9	2:01:20

The following subsections will summarize the experience gained by each participant during their 1A term, and work term (if applicable) above and beyond what was described in section 7.1. The analysis methods used in this chapter are consistent with those employed in Chapter 5 and described in section 4.2.1. As with Chapters 5 and 6 detailed analyses will only be presented for 5 out of 7 student participants. Jay and Jill's detailed descriptions and analyses can be found in Appendix E along with additional description of each participant's 1B experiences.

7.2.1 Chris

Chris was the first 4-stream student interviewed in May 2022. Chris remembered learning about constraints and criteria as part of the formal design process, and as a way to help make decisions, but the rest of the design teaching from ME 100 was not as easily remembered. Chris felt that most of the design instruction came from the DCAP part of the course; the lasting lessons from EGAD were mostly focussed on the CAD skills that he learned during the course. Chris had forgotten the hand sketching instruction he received in EGAD until prompted to think about it. Chris remembered enjoying the course more than his other 1A courses; he found the assignments were more interesting and so he was more motivated to complete them. When asked about open-ended projects in his 1A term, the toy project was the first thing that came to mind, though he remembered the phone stand project later in the interview. In reflecting on how he has changed since his first interview, Chris commented that he now knows how he should move through a design process, and that he has more CAD skills than before 1A.

The phone stand project taught Chris lessons on the particulars of designing for 3D printing, like thinking about the part orientation as it is printed and how that will impact the support material needed. When asked what the project taught him, he just reflected on the difficulty of meeting the project constraints (e.g. the amount of material they were permitted to use in their design). Chris did print his cell phone stand design, and realized when he tested it, that it didn't work for his specific phone (which had rounded edges and so would slip out of the stand).

Chris was in a group of 3 for his toy project. Their project idea was a water balloon launcher powered by compressed air that could shoot multiple water balloons in quick succession. Chris did not feel like the knowledge and skills taught in EGAD were particularly useful for the toy project; he felt that SolidWorks drawings are too time consuming to produce, and so their team relied on hand sketches to communicate design ideas. Chris' focus in the toy project was producing the final report, he commented that he only did 20-30% of the other work in the project. One other team member had prior experience with pneumatics, and so he took the lead on designing and constructing the toy prototype. In their project, pneumatics were chosen to power their toy because of the one group member who was familiar with it, and they thought it sounded interesting.

Chris also participated in the formula student team during his 1A term. He commented that the vehicle design was completed before he started at Waterloo, and so his task was to produce physical parts that the team had already designed. The team would give him SolidWorks drawings of a part, and Chris was to go to the machine shop to make that part. Chris produced parts using drill presses, and milling machines, but primarily with the lathes. Chris relied on the technical staff in the student machine shop to assist him with the manufacturing methods, commenting that their experience was invaluable in producing the parts. Chris commented that the parts were well designed, needing few or no modifications to produce them; the parts he was assigned to make were simpler than some of the other parts in the car, but working on them taught him lessons on how to translate drawings to a physical part. Chris did not participate in any other design events, nor work on any side projects on his own during his 1A term.

For Chris' co-op work term, he was employed with a sub-contractor at a major automotive assembly plant. His task for the work term was as a physical laborer: supplying parts to various stations on the assembly line as they needed them. The task was very clearly described to Chris, and he was expected to continue doing that same task each day during the work term. This position did not give him any opportunities to apply what he had learned in 1A, and when asked what he learned in his work term, he struggled to identify anything of relevance.

Table 34 summarizes Chris' knowledge development prior to the 1B interview. Chris' experiences with the engineering student team including the mentoring from the engineering student machine shop staff, and his discussions with the ME 100 teaching team about manufacturing his cell phone stand have added to his knowledge of various manufacturing processes including machining, and 3D printing.

Table 34 Updated knowledge development from experiences - Chris

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Limited knowledge of terminology and components of automotive domain	Interest in professional car racing; online videos and DIY vehicle maintenance; student design team	2. Understand - Explaining
	Knowledge of materials, design and construction tools of 3D printing	ME 100 cell phone stand	2. Understand - Explaining
Conceptual	Limited knowledge of component categories in automotive domain	Online videos and experience with DIY vehicle maintenance	3. Apply – Executing.
Procedural	Limited knowledge of automotive-specific skills, techniques	Online videos on DIY vehicle maintenance; student design team	3. Apply – Executing.
	Knowledge of machining and manufacturing processes	Waterloo automotive student team; co-op work term	3. Apply – Executing.
	Limited knowledge of procedures for converting part drawings into final products	Waterloo automotive student team	3. Apply – Executing.
	Limited knowledge of manufacturing with 3D printers	ME 100 cell phone stand	3. Apply – Executing.

Chris exhibited one unique trait during the interview that is worth discussing further. Throughout Chris' interview, it seemed that the only teaching activities he could recall were activities that were tied to an explicit assessment. For example, when asked to describe the decision-making process for their toy project, Chris had this to say: "So the way the project worked was like, um, they walked us through the design project quite a bit… they would have you come up with ideas, right? And then like… What was it? Like after you get your groups like chosen idea, you would have to consider like the criteria, constraints, and then you'd have to like submit a small assignment about what the criteria and constraints are."

7.2.2 Michelle

Michelle joined the formula motorsports team in 1A, but she commented that she was not able to really complete any work for the team as she grappled with the workload and adjustment to university life. Michelle felt that ME 100 gave her the experience of what engineering would be like and was surprised at the significant quantity of design experiences she had in ME 100. Michelle remembered the ME 100 lectures on design, the coffee maker dissection activity, the cell phone stand project in EGAD, and the toy project. Michelle was quite proud of the aesthetics of her cell phone stand, and she commented that she spent some time on her own continuing to work on her cell phone stand design. Michelle's toy project was a collectible toy that would launch a disk with a hidden character in it. When asked what part of the project she contributed to, she selected the task of writing the report; letting her teammates lead the sketching, design, and construction tasks. The last experience that Michelle mentioned was programming related: Michelle mentioned that she attempted to make a Rubik's cube solver in Python for a simplified 2x2 cube.

Table 35 shows an updated summary of Michelle's knowledge development. For clarity, knowledge taught in ME 100 is not included unless specifically mentioned by the participant, or in cases where they had existing knowledge of that type that has now improved. In Michelle's case, ME 100 built on her existing knowledge of manufacturing and mechanical engineering design processes.

Table 35 Updated knowledge development from experiences - Michelle

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Knowledge of beginner/intermediate software engineering concepts	Hackathons and Technovation	6. Create - producing
	Limited knowledge of terminology and components of automotive domain	Interest in professional car racing; Waterloo formula race car team	1. Remember
	Limited knowledge of manufacturing/machining concepts	Waterloo formula race car team; machine shop training	3. Apply - Implementing
Conceptual	Knowledge of beginner/intermediate software engineering principles	Hackathons and Technovation; university side project	6. Create - producing
Procedural	Knowledge of human-centered software engineering design process	Technovation	3. Apply - Implementing
	Limited knowledge of manufacturing/machining processes	Waterloo formula race car team; machine shop training	3. Apply - Implementing
	Knowledge of technical drawing and 3D CAD processes	ME 100; Waterloo formula race car team; university side project	6. Create - producing
	Knowledge of mechanical engineering design process	ME 100; First week of ME 101	3. Apply - Implementing

7.2.3 Patrick

During Patrick's 1A term, he was competing in a varsity sport at the university, which required significant time each week. Like Michelle and Jill, Patrick could not identify any design learning in 1A outside of what happened in ME 100; and his recollection was that most of the teaching and learning of design was in DCAP. His recollection of EGAD was very focussed on the CAD, and especially the SolidWorks skills that were taught in that section of the course. The only projects or activities that Patrick mentioned were the toy project, and the cell phone stand project (when asked about it). Patrick's toy project was a box full of water that could generate a large wave, simulating a tsunami. For the project, Patrick was involved in the decision-making processes of the team, but his primary contribution was to construct the box and the piston that would generate the wave. For Patrick's cell phone stand, unlike most students in EGAD who were only permitted to print one copy, Patrick was able to print a first version, make changes, and print a second updated version because he used his own printer at home. Patrick did not participate in any engineering-related extra-curriculars in his 1A term; however, he was able to complete some small 3D printed designs for his home wood shop.

Table 36 summarizes Patrick's knowledge development prior to his 1B interview. Patrick's 1A experiences relating to engineering were somewhat limited due to his involvement with varsity sports; the experiences he did have tended to build on existing strengths. For example, Patrick leveraged his knowledge of woodworking in the construction of his group's toy project prototype.

Table 36 Updated knowledge development from experiences - Patrick

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Knowledge of materials, design tools, and construction tools relating to woodworking	Self-driven hobby, YouTube instructional videos, experience in professional wood shop	6. Create – Producing
	Knowledge of materials, design tools, and construction tools relating to 3D printing	Self-driven hobby, YouTube instructional videos; ME 100 cell phone stand	6. Create – Producing
Conceptual	Knowledge of construction methods in woodworking	Self-driven hobby, YouTube videos, experience in professional wood shop	6. Create - Producing
Procedural	Knowledge of procedures for converting part drawings into final products in woodworking	Self-driven hobby, YouTube videos, experience in professional wood shop	4. Analyze - differentiating
	Knowledge of manufacturing with 3D printers	Side projects for home shop; ME 100	6. Create - Producing
	Knowledge of 3D CAD modelling	Side projects for home shop; ME 100	6. Create - Producing

7.2.4 Oscar

Oscar had a better memory for the course contents of ME 100 than most of the other participants. This included recognizing that activities like the coffee maker dissection and paper rocket activity were meant to teach them concepts related to mechanical design. He remembered learning about criteria and constraints and applying those concepts in the toy project. Oscar's toy project was a tower building game that included

Table 37 Updated knowledge development from experiences - Oscar

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Limited knowledge of woodworking materials, design and construction tools	Self-driven hobby	2. Understand – Explaining
	Knowledge of materials and components of robots	High school robotics team, summer employment; ME 100 toy project	6. Create - Producing
	Knowledge of beginner/intermediate software engineering concepts	Co-op work term	6. Create - Producing
Conceptual	Limited knowledge of construction methods in woodworking	Self-driven exploration of hobby, instructional videos	2. Understand – Explaining
	Knowledge of robotics systems	High school robotics team, summer employment; ME 100 toy project	6. Create - Producing
	Knowledge of 3D printer construction, setup, and operation	Co-op work term	5. Evaluate - Checking
	Knowledge of beginner/intermediate software engineering principles	Co-op work term	3. Apply - Executing
	Knowledge of common components of mechanical design	ME 100; co-op work term; university side project	5. Evaluate - Judging
Procedural	Knowledge of 3D CAD modelling	High school courses & robotics team, high school competition, summer employment, self-driven exploration; ME 100; co-op work term; university side project	3. Apply - Using
	Knowledge of machining and manufacturing processes	High school courses & robotics team, summer employment; co-op term; university side project	4. Analyze – Differentiating
	Knowledge of manufacturing with 3D printers, laser cutters	ME 100 cell phone stand; co-op work term; university side project	5. Evaluate - Judging
	Knowledge of design processes and design for manufacture	High school robotics team, summer employment; ME 100; co-op term	5. Evaluate - Checking

simulations of earthquakes to try and knock down your structure. Oscar's contribution to the project was to design and construct the spinning mass portion of the design that powered the simulation as well as to write the report. Oscar also recalled the cell phone stand project, including using SolidWorks to calculate a centre of mass for his design. Oscar did not participate in any extra-curricular activities in his 1A term, focussing instead on his studies. Oscar's co-op work term was with a makerspace on campus where he helped students and faculty members who came into the space and was responsible for maintaining the tools in the space. This frequently meant making repairs to equipment like 3D printers, and with giving advice to users of the space on how they can improve the manufacturability of their designs. Oscar had to learn some programming languages to support course projects that his group was supporting that term. During his winter work term, Oscar also expanded on his past research of the Antikythera mechanism, designed it in SolidWorks, and began manufacturing it using 3D printers and laser cutters.

Table 37 summarizes Oscar's knowledge prior to the 1B interview. Oscar's toy project and co-op work term reinforced his prior experience with robotics systems, and furthered his knowledge of design processes, manufacturing methods, and especially his knowledge of rapid prototyping tools and methods. Lastly, Oscar's side project of constructing the Antikythera mechanism – a complex mechanical system of gears – have furthered his knowledge of mechanical design components and manufacturing methods.

7.2.5 MJ

MJ found the content of ME 100 to be very useful during his winter co-op work term (especially the CAD skills). MJ didn't seem to remember the PRIMED design process that was taught in DCAP, but he remembered the concepts of criteria and constraints, and he was conscious of how those concepts were applied in ME 100. MJ remembered the cell phone stand project, and especially how it connected DCAP and EGAD, but he did not end up 3D printing his design. MJ's toy project was a mechanical, jumping frog that relied on mechanisms commonly found in mechanical clocks for its operation. MJ was involved in the prototyping and building as one of only two members in Waterloo that term, but he commented that the design choices were made by the other members of the group. As with Oscar, MJ felt that the toy project was more about report writing than design. MJ did not participate in any kinds of extra-curriculars in his first term. MJ's work term was an engineering position with a company that builds devices to monitor pipelines. MJ's role with the company included a variety of tasks including updating CAD drawings, manufacturing and assembly of parts and prototypes, and simple design tasks. During his work term, he was able to learn about electric motors, micro-controllers and Python, as well as skills like soldering.

Table 38 summarizes MJ's knowledge development prior to the 1B interview. MJ's second time in ME 100 likely strengthened his knowledge and skills of mechanical engineering design processes, and CAD modelling. MJ also would have benefited from the additional in-person experiences in fall 2021 (his first unsuccessful attempt in fall 2020 was fully remote). MJ did not participate in any extra-curricular activities, so his primary means for development were his co-op work term which taught him a wide array of knowledge and skills from different engineering disciplines including programming, electronics, and mechanical engineering.

Table 38 Updated knowledge development from experiences – MJ

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Knowledge of materials, design tools, and construction tools	Backyard zipline project, YouTube videos, parent/mentor involvement; ME 100; work term	5. Evaluate - Judging
	Limited knowledge of terminology and specific details of heavy machinery	Landscaping experience/training	2. Explaining
	Knowledge of electronic circuits and actuators	Co-op work term	3. Apply - Implementing
	Limited knowledge of software engineering concepts	Co-op work term	3. Apply - Implementing
Conceptual	Knowledge of common construction methods	zipline project, YouTube videos, parent/mentor; ME 100 toy project	6. Create – Producing
	Limited knowledge of component categories in heavy machinery	Experience/training with landscape equipment maintenance	3. Apply – Executing.
	Limited knowledge of electronic circuits and their layout and construction	Co-op work term	3. Apply - Implementing
	Limited knowledge of beginner/intermediate software engineering principles	Co-op work term	3. Apply - Implementing
Procedural	Knowledge of design processes	Shad Valley program, high school course, ME 100; co-op work term	3. Apply - Implementing
	Knowledge of 3D CAD modelling, sketching	ME 100; co-op work term	5. Evaluate - Judging
	Knowledge of electronics assembly processes and techniques	Co-op work term	3. Apply - Implementing
	Knowledge of entrepreneurship and business practices	Started his own landscape company, Shad Valley program	3. Apply - Implementing

7.3 Cross-Case Analysis

In general, the connection of several activities in ME 100 with mechanical engineering design was not that obvious to the students except for Oscar. In some cases, related activities like the keychain (which highlights machining and manufacturing) would be brought up by the participants, but generally, they only thought of the toy project and the cell phone stand. The cell phone stand was not of the same magnitude (either time invested, or marks assigned to it) as the toy project, so it is perhaps expected that it was not thought of when talking of projects in 1A. For the other activities, like the keychain, coffee maker dissection, and paper rocket activity, based on the discussion with the instructors, the connections to design were present and were often emphasized during the activity; nonetheless, few students connected what they learned in those activities to design more broadly. This phenomenon is interesting, in that these smaller activities and experiences represent the formative practice of design during the term, whereas the toy project is a summative activity. This means the students don't really perceive any formative practice of design; though some students seemed to have such a strong connection in their minds between learning CAD software and the act of designing, that learning one (i.e. CAD) meant that they were learning the other (design). While this was not verified by the course instructors, there could be a disconnect between the topics students are being asked to reflect on and the knowledge and skills of mechanical engineering design; it is common that the student assignments and/or reflections on these activities do not have the students think explicitly about what the activity taught them (about design, engineering more broadly, or otherwise). The assignments that tend to follow these activities have students focus on the outcome of the activity, or perhaps the process; often asking questions like “what worked about your design”, “what didn’t work”, or “what would you do differently next time”. All of these are valid questions to have students think about, but they don’t necessarily force students to think about the big picture of engineering design. This seemed to be backed up by the participants’ responses when asked what projects like the toy project or cell phone stand project taught them about design. Most participants were not expecting a question like this, and it was clear from their responses that they had not given it much thought prior to the interview (or perhaps have forgotten the lessons from these activities due to time).

All four 4-stream students were able to obtain co-op positions during the winter work term, however, it seems that only three out of four students with work terms had meaningful learning experiences (MJ, Oscar, and Jay). In some cases, these experiences reinforced their existing knowledge (e.g. Oscar’s knowledge of CAD and 3D printing), but frequently these co-op positions expanded their knowledge into new domains like electronics, programming, and manufacturing (e.g. with MJ and Jay). The work term should provide these students with a significant boost over their 8-Stream counterparts who had not yet had a work term placement. It can be expected that the learning during the co-op work term was more pronounced than from a single course. In a work term, students are spending 35 hours a week for 16 weeks at the employer (compared to 36 total hours of lecture in a typical university course), typically have a closer relationship with an expert (i.e. a manager likely has fewer than 10 subordinates, compared to a course instructor of a class of 110 students), and can better focus their attention as they are not trying to learn five different subject areas at the same time. The work term environment is much more conducive to the deliberate practice that leads to expertise development than even the best classroom environment; though this type of experience is not a guarantee, as can be seen with Chris’ work term.

Four students sought out co-curricular activities during their first term (Chris, Jill, Jay and Michelle), with Michelle confessing that she couldn’t contribute much to the student design team she joined due to her workload in fall. For the other three, their experiences with the student teams seemed to be beneficial, with all three discussing mentorship they had received from either campus technical staff (Chris), or from upper year undergraduate students who were supervising the various activities of the student team (Michelle and Jay). Across the seven participants in 1B, the differences between students’ levels of knowledge and experience appeared to have gotten smaller, though there was some evidence of the "rich getting richer", especially with 4-stream students who benefited from their work term (e.g. MJ and Oscar). However, two out of three 8-stream students were proactive in seeking out new experiences.

All seven participants were enrolled in a design course in 1B when they were interviewed the second time, however, the interviews in January happened a week later in the term than the interviews in May. This seemed to manifest in the 1B interviews as ME 101 knowledge only really came up with the 8-stream students who were interviewed in January. Generally, this showed up in the interviews when the students spoke of a problem's "requirements", instead of "criteria and constraints"; "problem requirements" is the language used in the 1B design course. This means the 8-Stream students had the benefit of learning more about an alternative design process to the one that was taught in 1A prior to their interview.

7.4 Summary of Findings

Similar to Chapter 5, the data presented in this section will be used in combination with the design activity analysis of the following chapter to investigate **RQ1** (What effects do knowledge and personal epistemology have on novice designers' design behaviours), and **RQ2** (What impact does one semester of design instruction have on novice designers' knowledge, personal epistemology, and design behaviours). The data in this section is nevertheless useful for exploring RQ2 before discussing participants' design behaviours. Table 39 summarizes the knowledge taught in ME 100 (EGAD and DCAP) based on the instructor interviews at the end of the course offering. The "relevance" column was removed here as relevance is assumed if it is part of the course.

Table 39 Summary of knowledge taught in ME 100

Factual		Conceptual		Procedural	
Domains	Level	Domains	Level	Domains	Level
Materials	Low	Mech. components	Low	Design	Medium
Manufacturing	Low	Construction	Low	Ideation methods	Low
3D printing	Low			Decision-making methods	Low
Design tools	Medium			CAD modelling	High
Construction tools	Low			Rapid prototyping methods	Medium
Crafting	Medium			Machining, manufacturing processes	Low

Based on the description from the course instructors, CAD modelling was a significant focus of instruction with multiple assignments and projects reinforcing student learning. Following this, design processes and rapid prototyping methods (3D printing and laser cutting) were a focus of the course instruction and were reinforced through activities and projects in ME 100. The projects in the term also gave students an extended opportunity to gain comfort and familiarity with design tools (e.g. sketching, design criteria and constraints, CAD) and simple manufacturing/crafting materials and tools. The other topics summarized in the table were present in lecture and/or in learning activities, but to a lesser extent.

When the student participants were asked what they remembered about learning design in 1A, there were topics that were easily remembered by all the participants like design constraints and criteria, learning CAD, and the toy project. The 8-Stream students all remembered the cell phone stand project, while it was not so easily remembered for the 4-Stream students. The 8-Stream students all 3D printed their phone stand (which was an optional step), whereas MJ in 4-Stream, at least, did not. Chris and Jay in 4-Stream also didn't remember the cell phone stand project right away, though they were able to talk about it to some extent once they were reminded of it. The other topics were not as universally remembered by the students; only a small number brought up the design lectures in DCAP (three participants in total), the coffee maker dissection and EGAD design tips (two participants), or the paper rocket and ideation activities (one participant each). It is possible that these learning activities were successful at instilling their respective lessons to the students without the students explicitly recalling them, though some of the students struggled to answer what some of the activities like the cell phone stand taught them about design when asked in the 1B interview.

Table 40 summarize the types of knowledge mentioned by the student participants in the 1A and 1B interviews. Procedural knowledge seems to have had the most opportunities for development, both in depth and breadth; however, most students gained additional factual and conceptual knowledge as well.

The next chapter of this thesis will examine the 1B design activity in detail, and the data presented there in combination with this chapter will seek to investigate **RQ1** and **RQ2**. The analysis of the 1B design activity will provide an opportunity to assess what knowledge (new or old) the participants were able to leverage when solving a representative mechanical engineering design problem.

Table 40 Summary of participant knowledge at time of 1B interview, 8-Stream indicated by 8-S, 4-Stream indicated by 4-S

	Factual			Conceptual			Procedural		
	Domains	Relevance	Level	Domains	Relevance	Level	Domains	Relevance	Level
Jill 8-S	Programming Airplanes Crafting 3D Printing	Low High Low Med	Med Low Med Med	Programming Airplanes Construction	Low High Low	Med Low High	Software design 3D printing Manufacturing CAD Modelling	Low Med High High	Med Med Low High
Patrick 8-S	Woodwork 3D printing	Low Med	High Med	Woodwork	Med	High	Manufacturing 3D printing CAD Modelling	High Med High	Med Med High
Michelle 8-S	Programming Automotive Manufacture	Low High High	Med Low Low	Programming	Low	Med	Software design Manufacturing CAD modelling Design	Low High High V. High	Med Low High Med
Chris 4-S	Automotive 3D printing	High High	Low Low	Automotive	High	Low	Automotive Manufacturing 3D Printing	Med High Med	Low Med Low
Jay 4-S	3D printing Electronics Composites	Med Low Med	Med Med Low	Electronics Mech. components	Low High	Med Low	CAD modelling 3D printing Electronics Design process Verification Composites	Med Med Low V. High High Med	High Low Med Med Med Low
MJ 4-S	Construction Machinery Electronics Programming	Med Med Low Low	Med Low Low Low	Construction Machinery Electronics Programming	Med Med Low Low	Med Low Low Low	Design CAD Modelling Electronics Entrepreneur.	V. High High Low Low	High High Low Med
Oscar 4-S	Woodworking Robotics Programming	Low High Low	Low High Low	Woodworking Robotics 3D Printers Programming Mech. components	Med High High Low High	Low High High Low Med	CAD modelling Manufacturing 3D Printing Design process	High High Med High	High High High High

8 Results - 1B Design Process Analysis

The middle section of each 1B interview with the student participants was a live design exercise where the participants gave a verbal protocol as they designed a device which enables a user to open a stuck double-hung window. The data presented in this chapter, in combination with the results from chapter 6 and 7 will enable the investigation into **RQ1** (What effects do knowledge and personal epistemology have on novice designers' design behaviours) and **RQ2** (What impact does one semester of design instruction have on novice designers' knowledge, personal epistemology, and design behaviours).

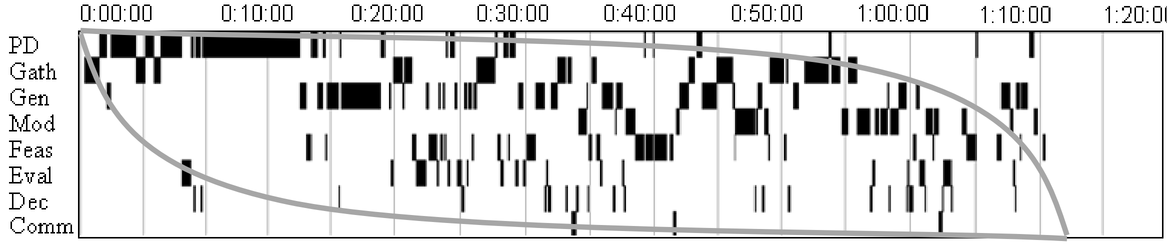
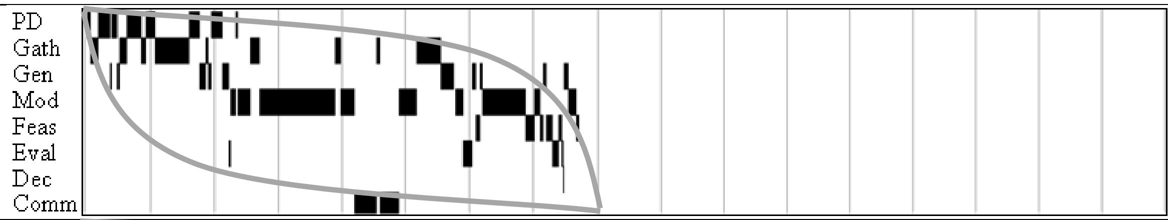
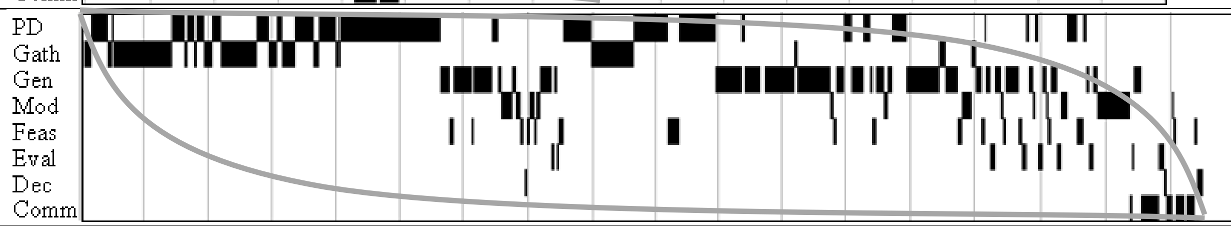
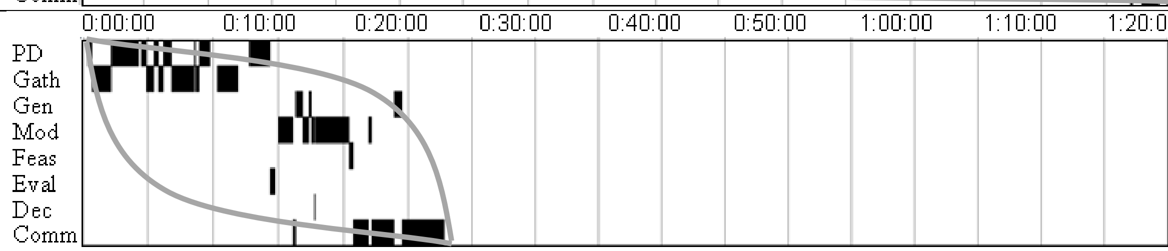
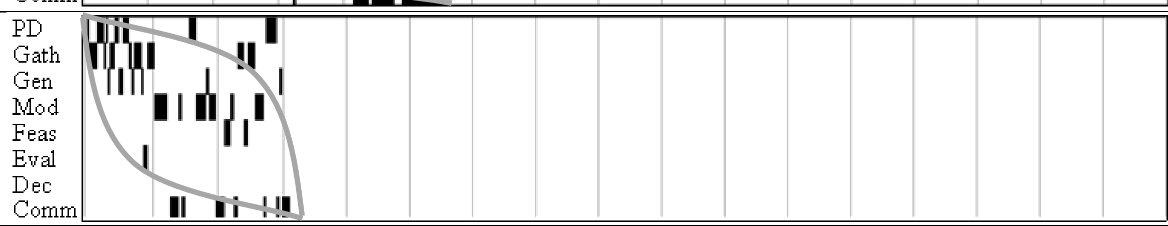
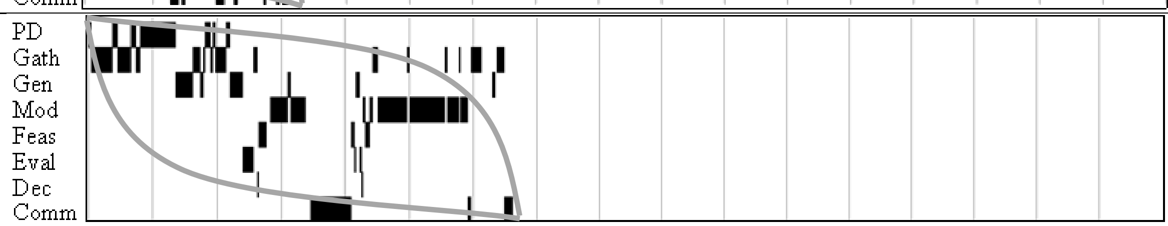
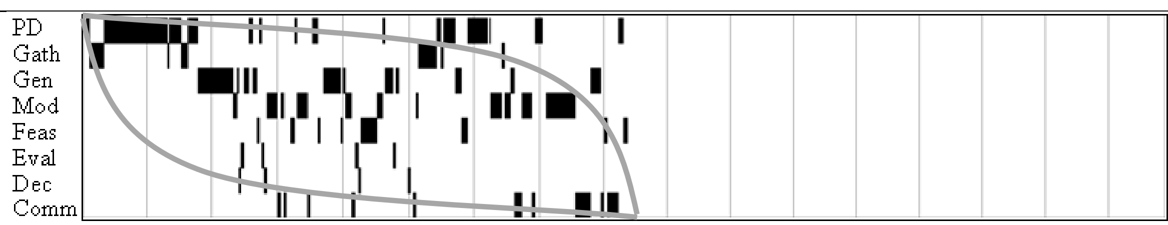
Prior to beginning the live design exercise, the students were given one shorter problem to practice thinking aloud as they worked through their solutions (see Appendix A for the full prompts). This verbal protocol was transcribed automatically using MS Teams and was verified and corrected before analysis began. The transcript was coded using the design step codes described by Atman and Bursic (1998). The result of this coding process are the timelines shown in Table 41 below. The cascade shape described by Atman (2019) has been superimposed over each timeline to enable a quick visual comparison of the participants' design process behaviour with the behaviour Atman describes for experts. The analysis methods used in this chapter are consistent with those used in Chapter 6 and described in detail in sections 4.2.2 and 4.2.3.

8.1 Preliminary Analysis of 1B Design Process

The student participants spent on average 45 minutes and 50 seconds on the design exercise (standard deviation was 24.0, a larger spread than the 1A interviews). During that time, the participants averaged 70 transitions between design process steps, at an average pace of 1.52 transitions per minute – a slower pace than the 1A interviews at 1.9. Overall, the students spent less time solving the problem in 1B than in 1A; only two students spent more than 40 minutes on the design activity in 1B (compared to four in 1A).

Detailed descriptions of all seven participant design timelines can be found in Appendix F. Additionally, as with Chapters 5, 6, and 7, detailed analyses will only be presented for 5 out of 7 student participants. Jay and Jill's detailed descriptions and analyses can be found in Appendix F along with additional detail of each participant's 1B design activity. Bond did not participate in the 1B round of interviews.

Table 41 Design timelines, 1B interviews

Michelle	
Jill	
Patrick	
Chris	
Jay	
Oscar	
MJ	

8.1.1 Chris

Chris completed the 1B design activity in 27 minutes and 49 seconds; an almost identical time to 1A where he took 27.5 minutes (Figure 16 shows Chris' 1B design timeline). In that time, he transitioned between design steps 27 times, at an average rate of 0.97 transitions/minute. This was lower than the 1B average of 70 transitions, and much lower than in his 1A interview where he transitioned between steps 50 times.

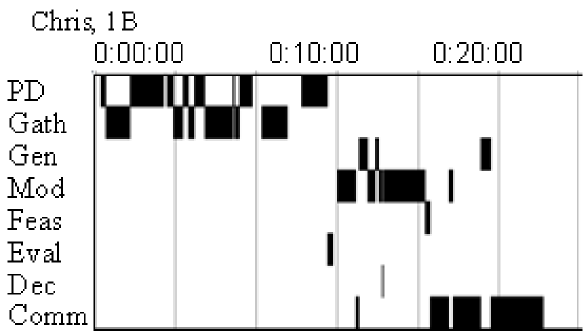


Figure 16 Design timeline of 1B interview with Chris

After a brief read of the problem statement, Chris immediately went to the internet to research double hung windows. When he found a site that described a double-hung window, Chris commented that he wasn't sure he had ever seen one in person before. Once he had an understanding of the operation of the window, he transitioned to writing down criteria and constraints for his solution. During this process, Chris realized he would need to assume what the user is physically capable of; he assumed that the user would only have the operation of a single arm/hand. He also made a simplifying assumption that by "stuck", the problem meant that the user was not able to operate the tilt latches for the window (section a in Figure 17). With the initial problem frame decided, Chris went back online to research the operation of the window latches. Chris clarified with the interviewer that he was allowed to set the parameters of the problem (i.e. that he can assume the user has the use of only one hand). At the 7-minute mark, Chris wanted to double check what "stuck" meant in the context of a double-hung window and searched online for more information on the types of issues these windows face. This research led him to comment that "there are so many ways a window can get stuck"; and so, he searched more on the types of latches that can be found on windows. Chris came across a window that had a sideways sliding latch on both sides of the window sash, realized that is likely the most difficult type for someone with only one hand to operate, and so decided that was the problem he was going to try and solve. With this, his problem parameters were fully decided: he was going to help a user that only has the use of one hand unlatch the double sliding latches that control the tilt operation in modern double hung windows (section b in Figure 17).

At the 10-minute mark, the interviewer asked Chris to show the type of latch he was designing for, which led to another round of online searches for window latches. This search took approximately 2 minutes, and then Chris began refining his criteria for a good solution – for example, it should be easy and comfortable to use, shouldn't damage the window, his device shouldn't block the view, etc. (section c in Figure 17). Just before the 15-minute mark, Chris thought of a solution that would have required replacing all or part of the window, and he decided he would stick to designing a device that would be installed on an existing window to save costs. Then at 15-minutes, Chris began sketching his solution. Chris' idea was to have two bars with hooks on the ends that would pull on the latches, with some kind of device in the centre that could simultaneously pull them both with one motion. During this section of sketching the details of his solution, Chris continued to speak but struggled to vocalize his thoughts; often resorting to describing what he was doing, and not what he was thinking. For example, at the 17-minute mark, Chris vocalized the following: "Let's see. Let's draw a little lever in the middle. Man, I used to be good at drawing what happened? Let's see, here's a lever. Oh, I think I know what to do now. um Let's see." This comment was coded as a decision, because even though Chris didn't describe what part of the solution he was working on; he clearly had some kind of realization of the direction he wanted to go with his solution. During the subsequent 2 minutes, Chris continued to sketch out details of his solution, without explicitly considering any alternatives, evaluating his solution, or vocalizing any decisions (section d in Figure 17).

Just past the 20-minute mark, Chris simulated the operation of his device to ensure that it would pull on both latches at the same time. After that, Chris presented his solution to the interviewer. As he was presenting, he realized he was missing a pin that would connect the handle mechanism to the window. After adding that, Chris began working on refined drawings of the parts of his solution including sketches of views from different perspectives. At around the 24-minute mark, Chris took some time to see if he could think of other alternatives to the device he designed. After about 30 seconds, Chris was satisfied with the solution he came up with and continued to produce finalized drawings of his design (section e in Figure 17). During this final stretch of sketching, Chris again struggled to speak his thoughts while drawing; he just idly described what he was drawing.

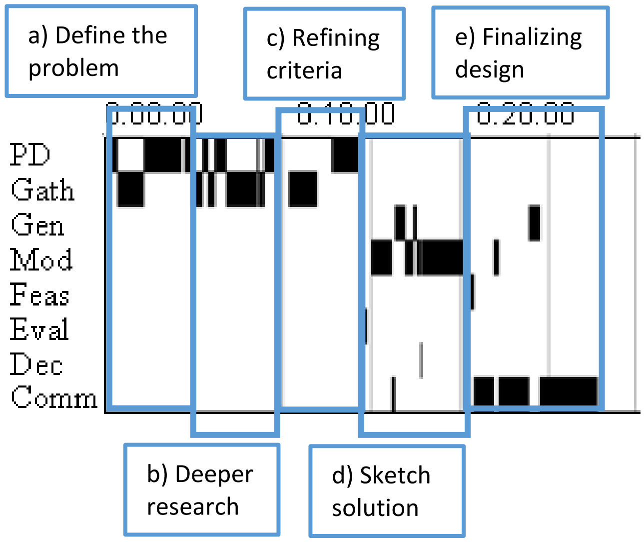


Figure 17 Overview of design process, 1B interview with Chris

Table 42 shows the percentage of time Chris spent in each step of the design process. Chris spent much more time in problem definition and information gathering in 1B compared to 1A, and much less time modelling and in feasibility analysis. Chris spent the largest percentage of his total time gathering information compared to the other participants but given that his overall design time was less than 28 minutes, many of the other participants spent more absolute time in that phase.

Table 42 Percent of time spent in each design step during 1B interviews, Chris highlighted

Design Phase	Michelle 1B	Jill 1B	Patrick 1B	**Chris 1A**	**Chris 1B**	Jay 1B	Oscar 1B	MJ 1B
Problem Definition	23%	14%	32%	**10%**	**23%**	19%	14%	29%
Gather Information	17%	20%	19%	**1%**	**22%**	21%	21%	8%
Generate Ideas	20%	9%	27%	**8%**	**5%**	7%	10%	18%
Model	11%	39%	8%	**37%**	**17%**	21%	29%	18%
Feasibility Analysis	10%	6%	5%	**10%**	**1%**	5%	4%	8%
Evaluation	7%	4%	3%	**1%**	**1%**	2%	3%	2%
Decision	4%	0%	1%	**1%**	**0%**	0%	0.5%	2%
Communication	1%	8%	4%	**23%**	**23%**	18%	12%	10%
Transitions (mean=70)	152	48	113	**50**	**27**	36	45	68

During Chris' interview, he picked up on the fact that this is a highly ill-structured problem space; there are a lot of variables (e.g. types of windows, types of disabilities). Chris recognized that he was going to have to make assumptions about the problem to be able to move forward. Many of these were reasonable, though he also made assumptions just to make the problem easier to solve. This could be the behaviour of a novice (i.e. treating the problem as well-defined) but he seemed to be self-aware of his choices and how they were making the problem easier. This could instead relate to Chris' motivation in this setting.

Interestingly, Chris' solution interacted with the tilt function of double-hung windows, and not the more typically used vertical sliding function. While he didn't comment on why this was his focus; this could be due to a lack of familiarity with these windows to the point where he didn't know that the sliding function is the more common interaction between the user and a double hung window. Nonetheless, assisting users with the tilt function would help with a stuck window, and so the interviewer did not intervene.

As with most of the other interviews, there were details left out of Chris' solution that would need to be corrected before his device could be manufactured. For example, Chris showed some of the fasteners that would hold the various pieces together, but he didn't really think through how it would attach to an existing window and didn't specify the materials, though he mentioned the parts could be made of aluminum at one point. Chris also seemed to recognize that he had no way of methodically evaluating his solution, so he just didn't. This seemed to be a consistent behaviour during his 1A project as well.

Examining Chris' 1B interview through the lens of Crismond and Adams, Chris showed some improvement from his 1A interview, but still showed many behaviours of a beginning designer:

- Chris took the time to research the problem before defining his criteria and constraints
- Chris researched the operation of double hung windows,
- generated a single design concept,
- designed a device that doesn't address the problem as presented (i.e. if the tilt mechanism was stuck, his device would not help the user free it),
- made decisions without weighing any options, and
- included little iteration or reflection during the process.

Chris' improvements from his 1A interview were mostly concentrated in the early parts of the design process – initial research on the problem and crafting design criteria and constraints. This coincides with the main lessons he recalled from ME 100, with only limited visible impacts of his other experiences. It does not seem like Chris was able to use the other knowledge he had acquired in 1A or in his work term.

8.1.2 Michelle

Michelle completed the live design activity in 75 minutes and 30 seconds, the second longest time of any of the students and transitioned between process steps 152 times – much higher than the average number of transitions of 70. This is more than three times as long as she spent in the 1A interview, with a much higher number of transitions (her 1A design activity took 26 minutes and 20 seconds and had 62 transitions).

Figure 18 shows an overview of Michelle's 1B design process. Michelle began by researching the operation of double-hung windows, and set the design constraints for her solution in section a. In section b, Michelle decided between a handheld solution, or one that is permanently mounted to the window, and then wrote detailed requirements for her solution in section c. Michelle created a first concept in section d before pursuing a robot solution that would keep the window tracks clean in section e. Realizing the window might still be stuck closed and need to be pried open, she pursued a third idea in section f. In section g, Michelle verified that her concept from section f would solve the problem and began refining it. In section h, Michelle worked on the detailed design of the device including materials and sub-components, finishing with specifying the required electrical components in section i.

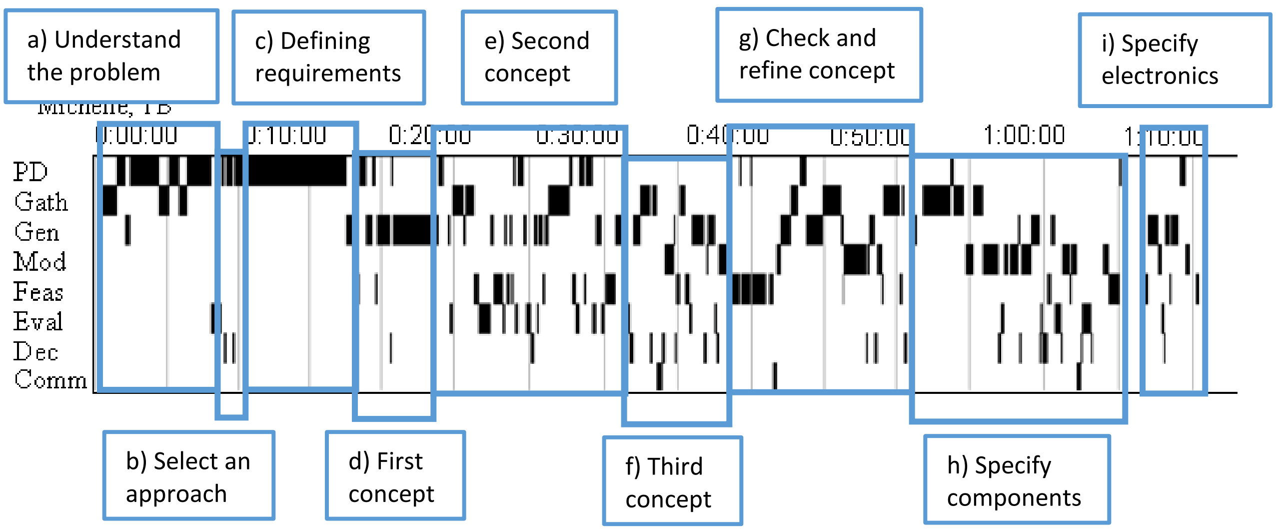


Figure 18 Overview of design process, 1B interview with Michelle

Table 43 summarizes the percentage of her total time that Michelle spent in each design step. Michelle spent a significant amount of time in problem definition, little time in modelling, and virtually no time in communication compared to her 1A interview (where she spent 1%, 38%, and 10% of her total time, respectively). Michelle spent a smaller percentage of time in modelling than any other participant except for Patrick. Michelle and Patrick spent 30 minutes more time designing than any of the other participants and so may have spent approximately the same amount of time modeling as the others.

Table 43 Percent of time spent in each design step during 1B interviews, Michelle highlighted

Design Phase	**Michelle 1A**	**Michelle 1B**	Jill 1B	Patrick 1B	Chris 1B	Jay 1B	Oscar 1B	MJ 1B
Problem Definition	**1%**	**23%**	14%	32%	23%	19%	14%	29%
Gather Information	**14%**	**17%**	20%	19%	22%	21%	21%	8%
Generate Ideas	**17%**	**20%**	9%	27%	5%	7%	10%	18%
Model	**38%**	**11%**	39%	8%	17%	21%	29%	18%
Feasibility Analysis	**3%**	**10%**	6%	5%	1%	5%	4%	8%
Evaluation	**5%**	**7%**	4%	3%	1%	2%	3%	2%
Decision	**4%**	**4%**	0%	1%	0%	0%	0.5%	2%
Communication	**10%**	**1%**	8%	4%	23%	18%	12%	10%
Transitions (mean=70)	**62**	**152**	48	113	27	36	45	68

Overall, Michelle's process in the 1B interview was quite different from 1A. Michelle's process in 1B wasn't overly strategic, or structured, but did more closely reflect the behaviours of an informed designer. Michelle considered different options throughout her process, not just in the main mechanism for opening the stuck window, but for smaller components as well, like how to attach her device to the window. Michelle also spent time setting up her initial requirements for the device (which she did not do in 1A). Michelle did initially struggle to think of what the device needed to do before she started thinking of solutions, but she revisited her requirements throughout her design process as she worked on her solution. Like several of the other participants, Michelle seemed to think that device requirements needed to be fully specified at the beginning and go unchanged for the duration of the design process; however, unlike many of the other participants, she did update the requirements as she better understood the problem and her solution. Michelle also did a good job operationalizing what safety meant in this problem context. For Michelle, this meant not only that the device would not damage the window, but that it was also safe to operate (which Michelle referred to as "stability" of the device throughout).

Michelle did not take the time to evaluate her third concept against earlier ones, she just moved ahead with the third one. Her decision for what family of solutions to pursue seemed to derive from her somewhat rigid understanding of the problem text, not what would be a "better" solution for the user. Michelle was able to leverage the procedural knowledge taught to her in ME 100 and ME 101, ultimately relying more on the language of design taught in ME 101. She was also able to see connections between the problem she was trying to solve and the knowledge she was going to learn in her 1B materials course. Interestingly, Michelle was not able to connect her math and physics knowledge to the design problem. She hit a point where she would need to do some modelling of forces to specify the strength of a motor and didn't even attempt it, though the calculation is fairly straightforward and well within her capabilities after taking physics in 1A. There were few obvious examples where Michelle used the factual or conceptual knowledge she has acquired since starting at university except for the scotch yoke mechanism taught to her in EGAD. Lastly, Michelle included electro-mechanical elements in her design in 1B (as she did in 1A) and struggled to specify the components she would need beyond the superficial ones (like an on/off switch). Her mechanical design also didn't show how these components would be physically installed in her device. As with the other participants, once her solution drifted into electrical components, Michelle struggled to complete those aspects of her design.

Comparing to the behaviours of a beginning designer described by Crismond and Adams, Michelle showed significant improvements from her behaviour in 1B:

- Michelle spent more time understanding the problem, and drafting device requirements,

- Michelle researched the problem early, and continued to look up information throughout,
- Michelle generated more than one concept for the main structure of her solution, and for the various sub-components within it,
- Michelle spent significant time in feasibility analysis and evaluation in 1B, though she avoided completing some of the analyses that she was capable of doing,
- Michelle designed a device that was missing a lot of detail, especially in the electro-mechanical aspects of the design, but which would be fully operable by someone with only one hand,
- Michelle spent more time in evaluation in 1B compared to 1A, especially when factoring in that Michelle spent an extra 50 minutes on the activity in 1B, and
- Michelle developed multiple concepts, and iterated on both her solution and on the problem frame

8.1.3 Patrick

Patrick spent 87 minutes and 25 seconds completing the 1B design activity, almost double his time of 49.5 minutes from 1A, and the longest design time of anyone in either interview. In that time, he transitioned 113 times; an almost identical number to the 112 transitions in his 1A interview (and much higher than the 1B average of 70).

Figure 19 shows an overview of Patrick's 1B design process. Patrick began by researching about double hung windows and reasons they might stick in section a, and then defined the problem as "how to keep the window tracks clean" in section b. In section c, Patrick brainstormed ways to keep dust and debris out of the window tracks, gathered more information online, and refined his design requirements. At the start of section d, Patrick decided to change his problem statement to designing a device that would force open a stuck window, and brainstormed options for applying a force to the window sash. In section e, Patrick discussed his alternative solutions, and in section f, he discarded the concept he created in sections b and c, moving forwards with the problem he described in section d. In section g, Patrick refined his solution.

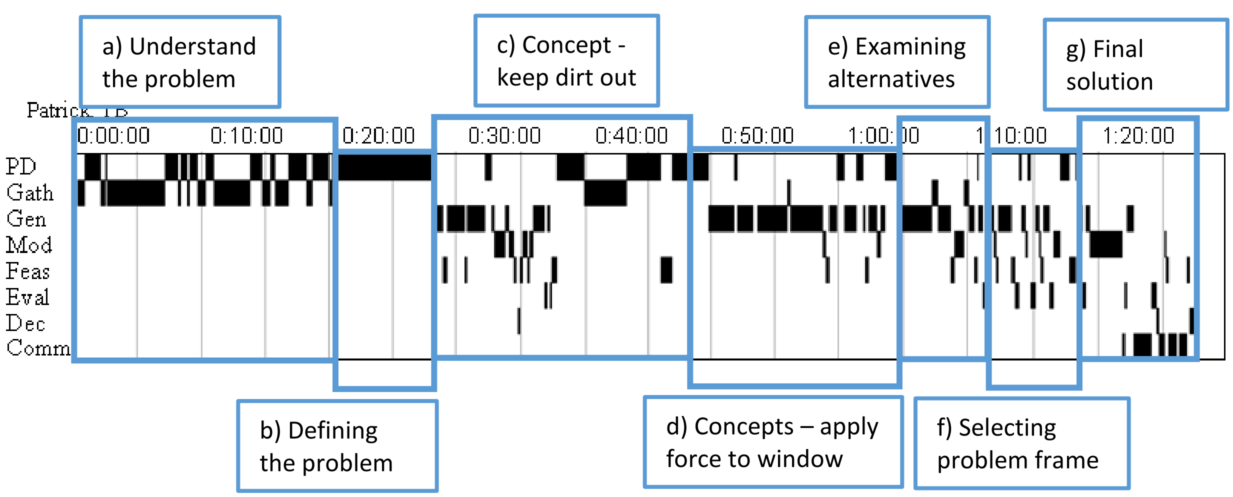


Figure 19 Overview of design process, 1B interview with Patrick

Table 44 shows the percentage of time Patrick spent in each phase of the design process. Compared to 1A, Patrick spent a higher proportion of time in problem definition in 1B, and a lower proportion of time gathering information or evaluating. Patrick spent more time than anyone in problem definition and idea generation in 1B (both as a percentage of his total time, and as an absolute amount of time), with problem definition, gathering information, and generating ideas representing 78% of his total design time.

Table 44 Percent of time spent in each design step during 1B interviews, Patrick highlighted

Design Phase	Michelle 1B	Jill 1B	**Patrick 1A**	**Patrick 1B**	Chris 1B	Jay 1B	Oscar 1B	MJ 1B
Problem Definition	23%	14%	**4%**	**32%**	23%	19%	14%	29%
Gather Information	17%	20%	**33%**	**19%**	22%	21%	21%	8%
Generate Ideas	20%	9%	**22%**	**27%**	5%	7%	10%	18%
Model	11%	39%	**2%**	**8%**	17%	21%	29%	18%
Feasibility Analysis	10%	6%	**5%**	**5%**	1%	5%	4%	8%
Evaluation	7%	4%	**15%**	**3%**	1%	2%	3%	2%
Decision	4%	0%	**3%**	**1%**	0%	0%	0.5%	2%
Communication	1%	8%	**3%**	**4%**	23%	18%	12%	10%
Transitions (mean=70)	152	48	**112**	**113**	27	36	45	68

Patrick's 1B process was quite unique among the participants of this study; his process might best be viewed as solving the problem twice: once with a focus on (re-)designing a window that avoids the problem of dirt accumulating in the slides, and once with a focus on applying more force to a stuck window to get it moving again. Patrick discussed some criteria and constraints for his solution as time went on, but he did not explicitly write any at the start of his process. It is possible that crafting some criteria and constraints could have helped him focus on what problem he was trying to solve, but he still may have pivoted to a different family of solutions as he did here. Explicit constraints may have also helped Patrick think about important design factors like user safety earlier. While Patrick did not have explicit design goals, he did revisit the problem statement throughout, leading to the pivot to the second type of solution. One of the side effects of this extended process was that it led to time management issues, especially when working on the second prybar solution. Patrick was starting to think of alternative shapes for the crowbar and then cut himself off. This seemed to be partly accelerating the pace of his designing, so he finished in 90 minutes, and partly because of a perceived lack of knowledge: "I don't think I have the knowledge or the time or the skill to be able to analytically design some new shape that's gonna be able to apply force correctly".

One of the more interesting changes from his 1A process was that Patrick wrote things down in 1B, including sketching along the way. This did seem to be a consequence of ME 100's instruction, though there were few other examples where Patrick directly referenced the knowledge taught in the course. Patrick also did much more research in 1B, for both trying to improve his understanding of the problem, and to help in designing his solutions (e.g. Patrick left pictures of double hung windows open on his computer throughout his process). Like in 1A, Patrick again seemed reluctant to make a choice so he could move forwards with his design. For example, at 1:41:00 he was still worried about a window tilted outwards but confessed he "[didn't] know why [that would be a problem], but that is not for me to decide." So, while Patrick's process had more traits consistent with an informed designer than 1A, it is harder to evaluate the direct impact of ME 100 on his design behaviours. This is perhaps due to a lack of new knowledge domains; the domains taught in ME 100 strongly overlapped with Patrick's existing pre-university experiences.

In 1B, Patrick showed more traits of an informed designer than in 1A:

- Patrick spent little time explicitly describing the boundaries or goals of the design problem, though he began thinking about criteria and constraints in the last 20 minutes or so of his process
- Patrick spent significant time researching the construction and operation of double hung windows
- Patrick revisited the original problem at several points in his design process, ultimately leading to him pivoting to a completely different type of solution,
- Like 1A, Patrick's solution might be a little awkward to use but would meet the intended purpose. Patrick ensured his device worked for windows that were either fully or partially closed
- Patrick came up with multiple options for his components, but his decisions were largely intuitive
- Patrick did reflect on how a user with limited mobility would use his device, as well as reflecting on how it could potentially damage the window,

8.1.4 Oscar

Oscar completed the 1B design activity in 33 minutes and 34 seconds, compared to 42 minutes and 50 seconds in 1A – well under the 1B average of 45 minutes and 50 seconds. In 1B, Oscar transitioned between design steps 45 times, for an average rate of 1.34 transitions/second. This is fewer transitions than his 1A interview where he transitioned between design steps 75 times, and lower than the 1B average of 70.

Figure 20 shows an overview of Oscar's 1B design process. In section a, Oscar researched the windows online, and then generated constraints and criteria for his solution in section b. In section c, Oscar generated some design concepts, and in section d, weighed their respective pros and cons and selected a crowbar-type device to pursue further. In section e, Oscar sketched his crowbar solution and presented it to the interviewer. In section f, Oscar thought about his solutions when the window is fully versus partially closed, leading to the development of a car jack-style solution in section g for when the window is partially open. In section h, Oscar researched the operation of the windows online and then presented his solutions.

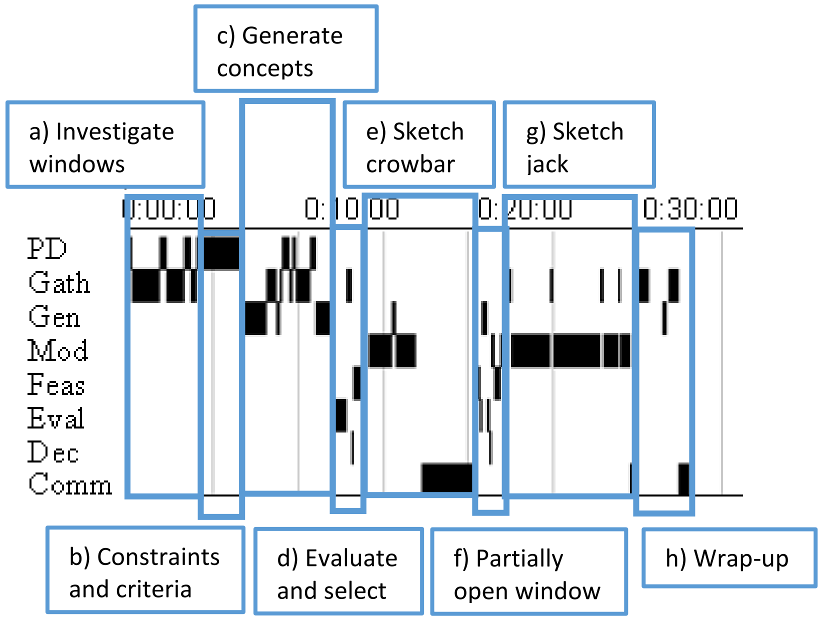


Figure 20 Overview of design process, 1B interview with Oscar

Table 45 shows the percentage of time Oscar spent in each phase of the design process. In 1B, Oscar spent more time in problem definition, and gathering information, and less time generating ideas, and evaluating compared to 1A. Across all categories, Oscar was not an outlier from the other participants.Oscar spent more time gathering information in 1B. This is partly because of the problem itself; Oscar was not as familiar with these windows as he was with the 1A problem, but some of it was spent searching for parts of his solution as well. Oscar also spent additional time in the problem definition phase in 1B, which seemed to be the result of ME 100, as he spent that time writing out criteria and constraints. Unfortunately, while Oscar wrote constraints and criteria, he never revisited them once he had started modeling his solution.

Table 45 Percent of time spent in each design step during 1B interviews, Oscar highlighted

Design Phase	Michelle 1B	Jill 1B	Patrick 1B	Chris 1B	Jay 1B	**Oscar 1A**	**Oscar 1B**	MJ 1B
Problem Definition	23%	14%	32%	23%	19%	**8%**	**14%**	29%
Gather Information	17%	20%	19%	22%	21%	**4%**	**21%**	8%
Generate Ideas	20%	9%	27%	5%	7%	**26%**	**10%**	18%
Model	11%	39%	8%	17%	21%	**29%**	**29%**	18%
Feasibility Analysis	10%	6%	5%	1%	5%	**4%**	**4%**	8%
Evaluation	7%	4%	3%	1%	2%	**10%**	**3%**	2%
Decision	4%	0%	1%	0%	0%	**0.4%**	**0.5%**	2%
Communication	1%	8%	4%	23%	18%	**14%**	**12%**	10%
Transitions (mean=70)	152	48	113	27	36	**75**	**45**	68

Interestingly, Oscar created two solutions to the problem that would be used at different times: one to get the window started, and one for when the window was partially open. Oscar did not think about ease of installation, which was especially relevant for his second solution (as the first one was a handheld device, and so didn't have to be installed). It is feasible that a mid-process cycle of checking his solutions against his criteria and constraints might have helped him identify this issue, but this step never occurred. Oscar may have been getting tired as the interview progressed as well, he spent more time thinking of possible solutions and the problem itself in the first half before he came up with the crowbar solution. He seemed to rush through the process of modeling the car jack solution when compared to his crowbar. There was some evidence of this from Oscar, himself, near the end of the design activity: "To be honest, my brain right now, like today isn't in the most like designing of moods. I hope that's OK."

Like Chris, Oscar struggled to talk while he was modeling his solutions, either going silent, or filling the silence with surface level description of what he was doing. During his modelling time, Oscar seemed to be more focussed on the quality of his drawings, than on the quality of his ideas. Oscar's comments on sketching, and use of constraints and criteria early in the process seemed to be a consequence of ME 100. Oscar did not seem to leverage what he learned in his work term, though if he were given the chance to construct a prototype, his experience with rapid prototyping would no doubt prove useful.

In 1B, Oscar showed more informed behaviours at some stages (like in the beginning of the design process), and some regressions at other stages (like in evaluation) when compared to 1A:

- Oscar spent time thinking about the problem, including writing out criteria and constraints
- Oscar did some searching of relevant information on windows, and on car jacks, though he did less evaluation of the information than in 1A
- Oscar thought about alternative solutions early on, but only generated two design concepts that would be used together to solve the problem,
- Oscar's second solution would be very challenging to install and use single-handed
- Oscar evaluated his prybar solution and realized it only works for a closed window, but otherwise did not evaluate his concepts, or compare his proposed solutions against his list of requirements
- Oscar made decisions with little evaluation, relying on his intuition
- Oscar iterated on a few details of his proposed crowbar solution as he progressed through modelling, but did very little iteration on his car jack design

8.1.5 MJ

MJ completed the 1B design activity in 41 minutes and 51 seconds, faster than his 1A interview time of 68 minutes and 18 seconds, and slightly under the average time for all participants in 1B. In 1B, MJ transitioned between design steps 68 times, much fewer than his 1A interview (148) but close to the 1B average of 70.

Figure 21 shows an overview of MJ's 1B design process. During section a, MJ thought about the users, and researched the operation of the windows. MJ was showing obvious signs of confusion, and so the interviewer clarified the wording of the design prompt. In section b, MJ wrote his design requirements and began brainstorming different components of his solution. In section d, MJ sketched a hand-cranked solution, and then brainstormed more concepts in section e. In section f, MJ refined the design of his initial concept, and then in section g, conducted some research on elements of his solution and updated his design requirements. In section h, MJ designed the vertical screw component of his solution, and in section i, MJ designed the based of his device that sat on the windowsill.

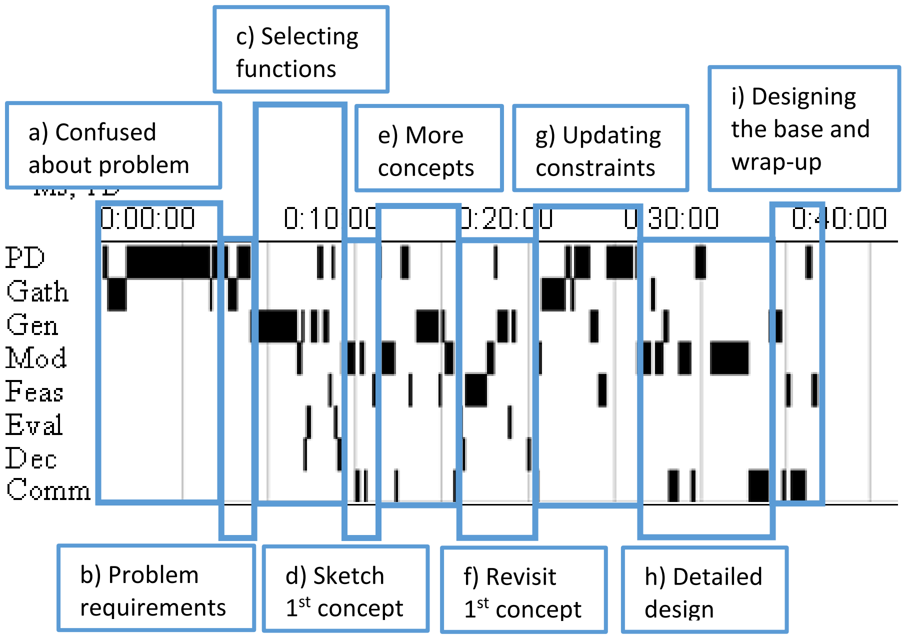


Figure 21 Overview of design process, 1B interview with MJ

Table 46 shows the percentage of time that MJ spent in each phase of the design process. Compared to 1A, MJ spent significantly more time in problem definition, and the same, or less time in all of the other phases. Only Patrick spent more time in problem definition than MJ in 1B, and MJ spent much less time gathering information than any of the other participants (as a percentage of his total time), but otherwise MJ fell within the typical range of the other participants.

MJ was initially confused about what the question was asking before the interviewer clarified the problem for him around seven minutes in. The interviewer picked up on this, both from his body language, and as MJ kept referring to the window as a "stuck double hung window". From this, it seemed he was thinking that was the proper name of the window, as opposed to the state (i.e. stuck) of the double hung window.

Table 46 Percent of time spent in each design step during 1B interviews, MJ highlighted

Design Phase	Michelle 1B	Jill 1B	Patrick 1B	Chris 1B	Jay 1B	Oscar 1B	**MJ 1A**	**MJ 1B**
Problem Definition	23%	14%	32%	23%	19%	14%	**6%**	**29%**
Gather Information	17%	20%	19%	22%	21%	21%	**13%**	**8%**
Generate Ideas	20%	9%	27%	5%	7%	10%	**20%**	**18%**
Model	11%	39%	8%	17%	21%	29%	**23%**	**18%**
Feasibility Analysis	10%	6%	5%	1%	5%	4%	**7%**	**8%**
Evaluation	7%	4%	3%	1%	2%	3%	**4%**	**2%**
Decision	4%	0%	1%	0%	0%	0.5%	**2%**	**2%**
Communication	1%	8%	4%	23%	18%	12%	**18%**	**10%**
Transitions (mean=70)	152	48	113	27	36	45	**148**	**68**

MJ broke his solution down into two components that he treated as two separate parts for ideation and modelling, before integrating them together. These two components were the mechanism for applying force to the window (the suction cup), and the mechanism for the user to interact with (the hand crank on the vertical screw). During ideation, MJ sketched different options and then checked the problem statement to make sure they would solve it. MJ also gave some conscious thought to how the user would install the device, something that was missing from most of the other interviews. Throughout the interview, MJ checked his solution against his requirements and was revising the requirements throughout the design exercise. One oversight of MJ's was the upper window sash in a double hung window. Like Jay, MJ chose to only interact with the bottom sash, but it was not a conscious choice with MJ, he seemed to forget that it was also operable (or perhaps he didn't understand that part of the window's operation).

During his design activity, MJ was evaluating his design, but he never made explicit what (if any) criteria he was using. Like most of the other participants, MJ's solution was missing details that would be required to manufacture the device (like the materials used), and he described parts of his solution but didn't show those sections in detail (for example, how the vertical screw intersects with the suction cup device). Missing details in his sketches that he talked about during the activity could be because of his perception of what the interview was looking for. He asked partway through what level of detail he would be required to show in his solution and seemed to interpret the response as just having to communicate his design ideas and not full manufacturing detail. Later in the interview, this showed up again as he was talking about cleaning up his final sketches: "Just make this look a little bit more professional, although I understand that as of the moment I'm just sketching for communication… I've learned a difference that sometimes it's it's not worth it to put that much time into a sketch." The idea of using sketches for communicating ideas, as opposed to producing polished drawings that accurately reflect the form of the solution was different from the others. For example, both Chris and Oscar were commenting on their drawing quality during their interview.

MJ was one of the few participants to bring up his 1B courses during the design activity. This manifested in two ways: mixing in the design process language of requirements from his 1B design course and talking about the knowledge he would learn in his materials course when he was thinking of what materials to use. MJ was able to leverage the procedural knowledge he was taught in ME 100 and in ME 101, both in his sketching behaviours, and in how he described the design goals early in the process. MJ did not seem to explicitly use the electronics knowledge he learned from his work term, though if he had made an electro-mechanical device like some of his peers, perhaps the knowledge he acquired would have been useful.

Examining MJ's design process through the lens of Crismond and Adams' patterns of behaviours, MJ behaved similarly to 1A, though he seemed to have more confidence in his approach (at least once he understood the problem) in 1B. This no doubt helped explain the quicker time to completion than in 1A. Otherwise, his behaviour was similar to 1A:

- MJ delayed making decisions on an approach for about 12 minutes, much less time than in 1A
- MJ searched online for useful information, especially about the operation of the window, and the suction cups he intended to use. He did not conduct any search of mechanisms that could be used
- MJ generated many possible solutions before deciding on his approach, and then generated three solutions to the his main sub-problem, ultimately combining different ideas into one solution
- MJ's conceptual sketch of his design was missing significant detail
- MJ weighed his options before deciding, but not through rigorous examination of the alternatives
- As in 1A, MJ completed many rapid iterations on solution concepts, refining the problem statement, and generating new concepts in the first half of the design activity; he did a better job in 1B at maintaining this reflection
- MJ revisited the problem statement frequently and did monitor his own thinking to a certain extent, recognizing when he ran out of the knowledge to proceed and trying a different approach.

8.2 Cross-Case Analysis

As in Chapter 6, the analyses of design processes and the impact of knowledge on design behaviours will be presented through two lenses: analysis of the design timelines (Atman, 2019), and analysis using Crismond and Adams' informed design teaching and learning matrix (Crismond & Adams, 2012).

8.2.1 Analysis of Design Timelines

Looking across the cases in 1B, there were some interesting patterns. Out of all the interviews conducted in any of the interview rounds, the shortest and longest design activities both took place in 1B (shortest by Jay and longest by Patrick). The average time taken in 1B was two minutes longer than in the 1A interview, which could be explained (at least in part) by every participant needing to look up what a double-hung window is, and how it operates in 1B. The standard deviation of design time was also larger in 1B than in 1A (24.0 versus 19.1 in 1A). Removing Patrick's outlier 1B interview from the calculation (because he nearly doubled his time taken in 1B) drops the standard deviation to 18.4 which is very close to the 1A value of 19.1. In his 1B interview, Patrick ended up solving the problem twice using two different interpretations of the problem statement. It is difficult to know for certain if this was a deliberate tactic to explore the field of solutions; it seemed to be the result of an ad hoc process and perhaps misinterpreting the problem statement. Ignoring this outlier, the average time taken and the standard deviation in times in 1B were similar to 1A, though the participants transitioned between steps fewer times in 1B (70 versus an average of 83 transitions in 1A) and at a slower rate (1.52 transitions/minute versus 1.9 transitions/minute in 1A). It is difficult to say what the cause of this was, though fatigue was an issue with some of the participants in 1B (Oscar notably talked about this). It is also possible that the participants were more deliberate with their process and so slowed down their transitions in the 1B interview, relying less on intuitive, system 1 thinking in 1B after their university experiences.

Reflecting on the behaviours of graduating students as described by Atman, there were some improvements in the 1B interviews. Table 47 summarizes the change for each participant in the 1B design activity compared to 1A. All participants except Jill spent a larger percentage of their time in problem definition in 1B compared to 1A (Jill spent approximately 15% of her total time in this step in both interviews, which made her an outlier in 1A where the others spent an average of 8%). Nearly all participants spent time writing some version of constraints/criteria, or requirements before solving the problem. All participants but Patrick spent a larger percentage of time gathering information in 1B, at least in part because everyone had to look up the operation of a double hung window in 1B. It should be noted that Patrick's 1A design activity was an outlier in this regard; he spent 33% of his total time gathering information in the 1A design activity, whereas he only spent 19% of his time there in 1B (Patrick's 1B behaviour is much more in line with the other participants who spent an average of 18%). Time spent in decision making and communication was mixed in 1B; Michelle and Jay spent much more time (as a percentage of the total) in these two steps in 1B; however, the rest spent about the same, or less time in these two steps. Michelle and Patrick spent much more time on their solutions in 1B, Jill spent about 90 seconds longer on her solution in 1B, while the rest spent the same or less time. Michelle and Jill had more transitions in 1B; however, the remaining participants had the same (Patrick) or fewer (everyone else).

Looking across these behaviours, Michelle showed the most significant difference, acting more akin to a senior student/expert in all five measures in 1B; Jill and Jay in three of these measures; Patrick, Chris and Oscar in two of these measures; and MJ in one of these measures. Some care is required in only examining these changes from 1A to 1B as these are somewhat crude measurements of some of the behaviours that Atman described, and outliers or high performing students in 1A may appear to regress in their behaviours.

For example, Patrick and MJ spent a smaller percentage of time gathering information, making decisions, and in communication in 1B, and had a slower rate of transitions in 1B compared to 1A; however, as already mentioned, Patrick spent a similar percentage of his overall time in information gathering in 1B as the other students, and MJ spent the same amount of time in decision-making and communication as the average of all the student participants in 1B (12%). This is nonetheless a useful summary of the changes in behaviour from 1A to 1B.

Table 47 Summary of changes in behaviour in 1B design activity, by participant

Participant	**% time in problem def'n**	**% time in info gathering**	**% time in decision/comm.**	**Total time spent**	**Transitions**
Michelle	Much higher in 1B	Slightly higher in 1B	Much higher in 1B	Much more in 1B	Much higher in 1B
Jill	Same	Higher in 1B	Slightly lower in 1B	Slightly more in 1B	Slightly higher in 1B
Patrick	Much higher in 1B	Much lower in 1B	Slightly lower in 1B	Much more in 1B	Same
Chris	Much higher in 1B	Much higher in 1B	Same	Same	Much lower in 1B
Jay	Much higher in 1B	Higher in 1B	Much higher in 1B	Less in 1B	Much lower in 1B
Oscar	Higher in 1B	Much higher in 1B	Lower in 1B	Less in 1B	Much lower in 1B
MJ	Much higher in 1B	Lower in 1B	Much lower in 1B	Much less in 1B	Much lower in 1B

8.2.2 Analysis of Informed Design Behaviours

To highlight the differences in performance between the participants in the 1B interviews Figure 22 and Figure 23 map student performance against indicators of informed designer behaviours as described in section 6.13 for the 1B 8-Stream and 4-Stream interviews, respectively. For the "Build knowledge" design strategy, two behaviours were selected: researching the problem space and researching the solution space. This choice was made because of the behaviour of the participants in the 1B interviews: with no exceptions, every participant researched the problem space in the 1B interview as they were not familiar with what a double-hung window was, or how it operated. In this way, it seemed to be the problem that was posed that was driving the behaviour of the participants and not something intrinsic to their knowledge, experience, or personal epistemology. Researching parts of the solution was not as universal a behaviour, and so there may have been differences in which participants were engaging in that behaviour, necessitating that it be isolated from those who only researched the problem.

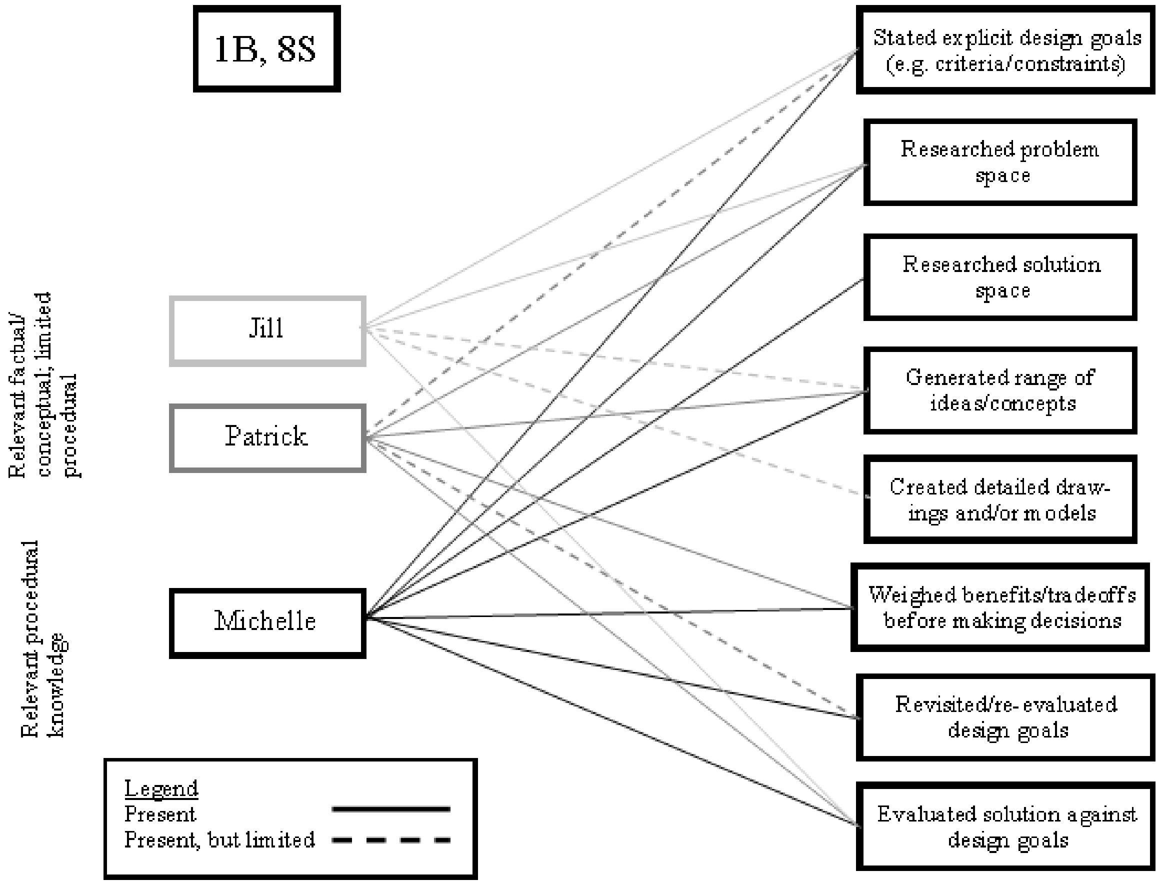


Figure 22 Map of student performance against indicators of informed design behaviour, 8-Stream students 1B interview

For the 8-Stream students, the level of pre-university knowledge seems to correlate to the number of informed design behaviours demonstrated by the participants. In order of most to least pre-university experience, Michelle demonstrated seven of eight behaviours; Patrick demonstrated six (two partially), and Jill demonstrated five (two partially). This pattern continues for the 4-Stream students, where in order of most to least pre-university experience, Oscar demonstrated all eight behaviours (4 partially), MJ demonstrated all eight behaviours (one partially), Jay demonstrated four behaviours (three partially), and Chris demonstrated four behaviours (one partially). There does not seem to be much evidence that 4-Stream students are out-performing 8-Stream students in this measurement. Interestingly, the more experienced 4-Stream students (MJ and Oscar) improved from their 1A interview, while the less experienced 4-Stream students had a more mixed result (Chris improved, Jay regressed), and all 8-Stream participants demonstrated more informed design behaviours than Chris and Jay. The 8-Stream students also generally spent longer on their solutions than the 4-Stream students; the two longest design activities (Michelle and Patrick) were both 8-Stream students, while the two shortest (Chris and Jay) were both 4-Stream. Jill (8-Stream) spent more time than Oscar (4-Stream), but slightly less time than MJ (4-Stream).

Except for Chris who spent about the same amount of time in 1B, all the 4-Stream students spent less time on their solution than in 1A, whereas all three 8-Stream students spent more time in 1B than in 1A.

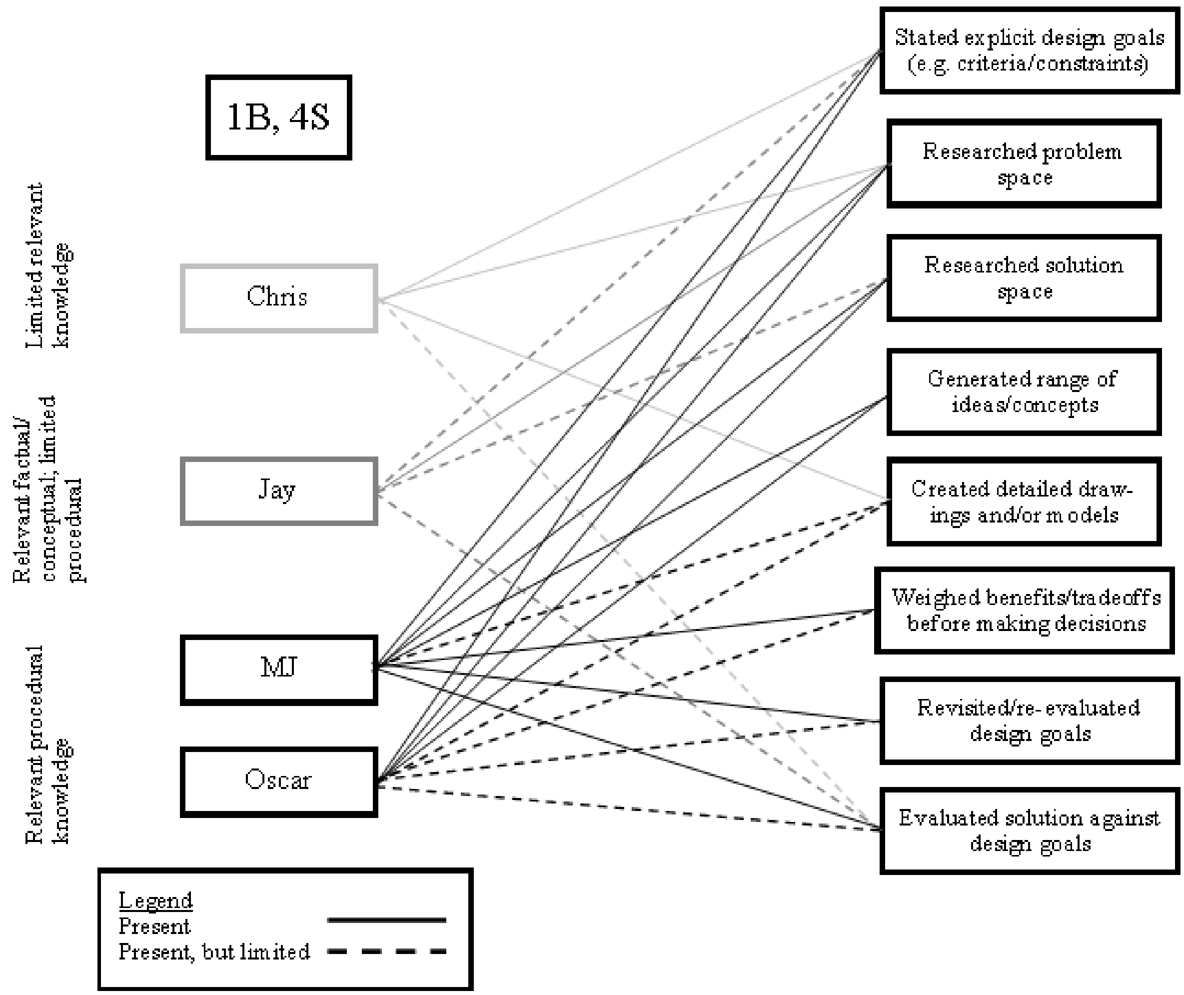


Figure 23 Map of student performance against indicators of informed design behaviour, 4-Stream students 1B interview

Some other observations can be made from Figure 22 and Figure 23. The behaviours from least common to most common are researching the solution space, creating detailed drawings/models, weighing benefits/trade-offs, and re-visiting design goals (four students each); generating a range of concepts (five students); and stating design goals, researching problem space, and evaluating solution against goals (all seven students). This is generally an improvement over 1A where only a single student weighed benefits/trade-offs, and only three created detailed drawings.

8.2.3 Other Observations

As in 1A, the participants struggled with finding useful information online, especially information that related to their solutions. For example, most were able to find details on the windows themselves, but other searches for strength of materials (e.g. Michelle) or manufacturing methods (e.g. Patrick) didn't produce much useful information. They also frequently asked the interviewer to clarify how the windows worked instead of finding the answer themselves (e.g. Jill, Chris, and Jay on multiple occasions). Overall, there may have been fewer examples of people totally lost when looking online; however, fewer people researched the solution space in 1B (four versus seven in 1A), and even the more experienced students struggled with finding helpful information for the solution space (MJ, Patrick).

The students in 1B generally still did not produce fully specified designs that were ready for manufacture. Interestingly, not one participant thought about using CAD software to help with their design. Perhaps this was because they didn't think it was allowed, or perhaps they felt they didn't have the time, but no one even asked permission to try it. It is also possible that even though the design activity instructed students to produce a design that was ready for manufacture, they treated the activity as a conceptual design exercise. The reasons could differ for different students as well; for example, Chris discussed SolidWorks in the debrief of his 1B interview where he struggled to communicate the value of the tool to his process, while MJ seemed to treat the entire exercise as conceptual design and so perhaps didn't see the need to specify details in his design. The absence of a requirement to construct a prototype of their solution during the design activity could have contributed to this view as well. Electro-mechanical elements also continued to be a struggle for the participants. Jill and Michelle both included electric actuators as part of their solutions, and these components were not well specified or described, and many details were missing.

There was little evidence of application of knowledge from any course outside of ME 100 in the 1B interview. There was virtually no numerical analysis of any kind during any of the 1B interviews, even where the calculations were simple and well within their experience after taking physics and math courses in 1A. Interestingly, there were more mentions of 1B courses (e.g. the materials course in 1B), than any of their other 1A courses. The students may have struggled to connect the more abstract physics, chemistry, and math courses from 1A to mechanical engineering design, whereas they perhaps saw more utility in their materials course in 1B even though they were only a couple weeks into the term. Michelle spoke with some frustration about this when trying to determine the force required to open a stuck window: "like opening windows, like how much force you need. What is that like? How… are we supposed to do anything with Newtons when nothing is ever measured in Newtons?" Of the knowledge taught in ME 100, a scotch yoke mechanism came up in several interviews and was a key part of Michelle's and Jill's solutions. Criteria and constraints were also frequently mentioned. There was little evidence of knowledge gained through either work terms or student design teams in any interview, though had MJ included electronics, for example, their knowledge may have had more relevance.

As summarized in Table 32 in Chapter 7, there was much less explicit instruction of conceptual knowledge than of procedural knowledge in ME 100. Where it was present, it seemed to have an outsized impact on student solutions – for example, multiple students used the scotch yoke mechanism that was introduced in EGAD in their 1B design activity. Oscar picked up on this in his 1B debrief near the end of the interview: "Honestly, a lot of this stuff I wish that I learned from design courses was like more technical applications. So far, I've had no indication that they plan on teaching us many like mechanisms and mechanism design in general, like gears… and I think that's something that I'm really interested in… but they haven't taught it"

The students in 1B also continued to struggle with vocalizing their thoughts as they designed. This was evident in participants with all levels of prior experience; Chris, Jill, and Oscar all struggled with this to varying degrees during the design activity.

8.3 Summary of Findings

The data presented in this chapter were used to explore the effects of knowledge on novice design behaviour after students have completed one semester of university-level instruction, and also after students have completed one four-month co-operative work term placement. The data from this chapter that relate to **RQ1** will be summarised first, followed by a discussion of the findings that relate to **RQ2**. Data from Chapter 7 of this thesis may also be included, where relevant.

8.3.1 Effects of Knowledge on Novice Designers' Design Behaviours

Summarizing the student design processes through the lens of Atman's design timelines (Atman, 2019), the following observations can be made:

- A lack of knowledge of the problem space may have caused a change in student behaviour in the 1B design activity; students spent more time gathering information in 1B than in 1A, which seemed to be driven by a lower level of familiarity with the problem space.

Summarizing the student design processes through the lens of Crismond and Adams (2012), the following observations can be made:

- The least common informed design behaviours in 1B were researching the solution space, creating detailed drawings/models, weighing benefits/trade-offs before making decisions, and revisiting design goals (only four students demonstrated each of these behaviours),
- The most common informed design behaviours in 1B were stating design goals, researching the problem space, and evaluating the solution against design goals; all of which were demonstrated by all seven student participants
- Consistent with the 1A design activity, the students with higher levels of pre-university knowledge demonstrated more informed design behaviours than students with lower levels of pre-university knowledge

- The informed design behaviours of weighing benefits/trade-offs and re-evaluating design goals were only demonstrated by Patrick, and the three students with relevant procedural knowledge from their pre-university experiences

Lastly, there was little evidence of the students applying knowledge from their 1A term outside of what was taught in DCAP. Even EGAD seemed to have only a limited direct impact on the students' 1B behaviours, for example, there was little evidence of a change in how the students engaged with sketching/drawing in 1B, except with Patrick who did not write or draw anything during the 1A activity; and no students attempted to use, or even asked to use, CAD software during the design activity. Still, some of the conceptual knowledge taught in EGAD did appear in the 1B design activities. The instruction in DCAP is most visible in the extra time the students spent in problem formulation, and by extension, in stating explicit design goals.

8.3.2 Impact of One Semester of Design Instruction on Novice Designers' Knowledge and Design Behaviours

Summarizing the student design processes through the lens of Atman's design timelines (Atman, 2019), the following observations can be made:

- Students spent on average approximately the same time solving the design problem in 1B as in 1A, but the standard deviation for time spent on the problem was much higher (24 vs. 19 in 1A) with 8-Stream students spending more time on the design activity than 4-Stream students
- Students spent more time on problem definition in 1B than in 1A, with nearly all participants spending time writing explicit constraints/criteria or project requirements as taught in their first-year design courses

Summarizing the student design processes through the lens of Crismond and Adams (2012), the following observations can be made:

- There were minimal differences in the number of informed behaviours demonstrated by 4-Stream students after their 4-month co-op work term, and 8-Stream students who were interviewed only a few weeks after the end of their 1A term; the number of behaviours demonstrated seemed to correlate more strongly with pre-university experience than stream or work term relevance/quality
- 8-Stream students generally spent more time on the design activity than 4-Stream students and generally spent more time on the design activity than they did in 1A.
- More students demonstrated the informed design behaviours of researching the problem space, weighing benefits/trade-offs, and creating details drawings/models in 1B than in 1A
- Fewer students researched the solution space in 1B than in 1A (four in 1B vs. seven in 1A)
- In 1A, students with relevant procedural knowledge were more likely to research the problem space, create detailed drawings, and weigh benefits/trade-offs before making a decision; whereas in 1B, these students were more likely to weigh benefits/trade-offs and re-evaluate design goals than their peers with less pre-university experience
    - In 1A, three of eight students created detailed drawings (Chris, Bond, Oscar), while in 1B, four of seven students created detailed drawings (Chris, Jill, MJ, Oscar)

- Three of the four students who created detailed drawings in 1B were 4-Stream students. This could have been a result of their work terms where detailed drawings would be more commonly seen, or it could be the result of a higher level of pre-university experience in the 4-Stream students (MJ and Oscar were both 4-Stream and were the two most experienced students)

A balance of factual, conceptual, and procedural knowledge is needed. Without the vocabulary of mechanical engineering design that comes with factual and conceptual knowledge of the domain, generating feasible design alternatives is challenging. This was perhaps most noticeable when students drifted into electro-mechanical solutions where they did not possess the necessary factual or conceptual knowledge of the domain, but it was also visible in their online searches for useful information. This vocabulary is also crucial in facilitating information searches for ideas in the solution space of the problem. It seems possible that ME 100 in the hybrid-delivered course in fall 2021 did not quite have the balance right, skewing more towards learning of procedural knowledge. This was no doubt impacted by the pandemic-era restrictions that reduced hands-on learning, and the course topics were reduced to better match the teaching environment and capabilities of the students.

Lastly, it is worth mentioning the significant improvement in the performance of Michelle in her 1B design activity. As mentioned in Chapter 6, Michelle was an outlier among the students with relevant procedural knowledge from their pre-university experiences, generally underperforming her peers in the same knowledge grouping. As shown in Table 47, Michelle was the only student to show an improvement in all five measures of experienced designers; and she improved from demonstrating five behaviours of informed designers (three of them partially) in 1A, to demonstrating all seven (except for creating detailed drawings/models in 1B). It is not clear what the cause of this improvement was, as she did not have a work term experience and took part in only a minimal number of extra-curricular activities in 1A. Perhaps as stated earlier, she underperformed in 1A for some reason; or perhaps something in her 1A experience resonated with her or was able to build off her prior experience with software design; or perhaps there was some improvement in her motivation or confidence coming into 1B that led to the improvement. Unfortunately, with the data available, little can be said definitively.

9 Results – Personal Epistemological Development

This chapter will present data on student personal epistemology demonstrated in the 1A and 1B interviews, as well as an analysis of the potential for personal epistemological development in ME 100 in fall 2021. These data will contribute to the investigation of **RQ1** (What effects do knowledge and personal epistemology have on novice designers' design behaviours) and **RQ2** (What impact does one semester of design instruction have on novice designers' knowledge, personal epistemology, and design behaviours). The discussion on **RQ3** (What is the interaction between knowledge and personal epistemology while designing) will be left to Chapter 10 of this thesis. As with previous chapters, this chapter will move through the interviews chronologically, starting with the 1A student interviews, then the instructor interviews, ending with the 1B student interviews.

9.1 Preliminary Analysis of Personal Epistemological Development – 1A

This section will present data and analyses of the 1A student interviews to investigate **RQ1**. The data were drawn from all three sections of the student interviews: the background section, design activity, and reflective debrief section. Details from student backgrounds that relate to opportunities for personal epistemological development are described to provide an understanding for the quantity and nature of activities which may have helped the participants develop their personal epistemology. Details of the design activity and debrief section are then discussed where student behaviours and/or comments revealed aspects of their thinking. Full detail on the analysis methods used can be found in section 4.2.4.

As with Chapters 5-8, detailed analyses will only be presented for five out of eight student participants. Jay, Bond, and Jill's detailed descriptions and analysis can be found in Appendix G.

9.1.1 Chris

Chris could not describe any pre-university experiences that he felt prepared him for engineering. He discussed private art and music classes, but from his description, these sounded well-structured and aimed at training the fundamental skills of the discipline. It is likely then, that he has not benefited from teaching and learning environments with an epistemic climate aimed at promoting personal epistemological development. During the 1A design activity, there was little evidence of reflective thinking; Chris only developed a single concept (though he developed it to a high level of detail). At one point, he rhetorically asked if he needed to come up with more than a single solution, though he opted not to pursue that line of thinking any further. Chris' solution leveraged his experience in automotive maintenance by including an oil filter wrench as the core component of the design. This ultimately was the first idea that came to mind, and he opted not to pursue other approaches.

During the post-activity reflection, Chris agreed that the problem had more than one possible solution, even though he didn't pursue them. When asked how he knew he had found a "good solution" to the problem, Chris commented: "I imagined using it and… it worked in my imagination, so I was like OK, let's go with this." Chris recognized several decisions made during the design activity including the type of force to apply to the lid (a prying force), how to secure the jar in the device (the oil filter wrench design), and material choices (e.g. the hinge should be metal "because hinges are made of metal"). When asked how he would justify his choice of prying action for the device to a boss, Chris seemed surprised that he would need to justify a choice he made, and was not able to provide a strong justification for the choice: "Uhm? I never thought of it this way that might have been something to consider when designing it, UM. Justify it, well, because the seal on the jar, right, is tight enough ... You typically have to pry it in some way to pop it open." Overall, Chris was able to see the uncertainty in the question, even though he only presented a single design concept, and did not see a need to justify choices he made in the design activity. It would appear that Chris is exhibiting what King and Kitchener (1994) described as pre-reflective thinking (level three), perhaps stretching into quasi-reflective thinking (level four) when pressed to justify a decision he made.

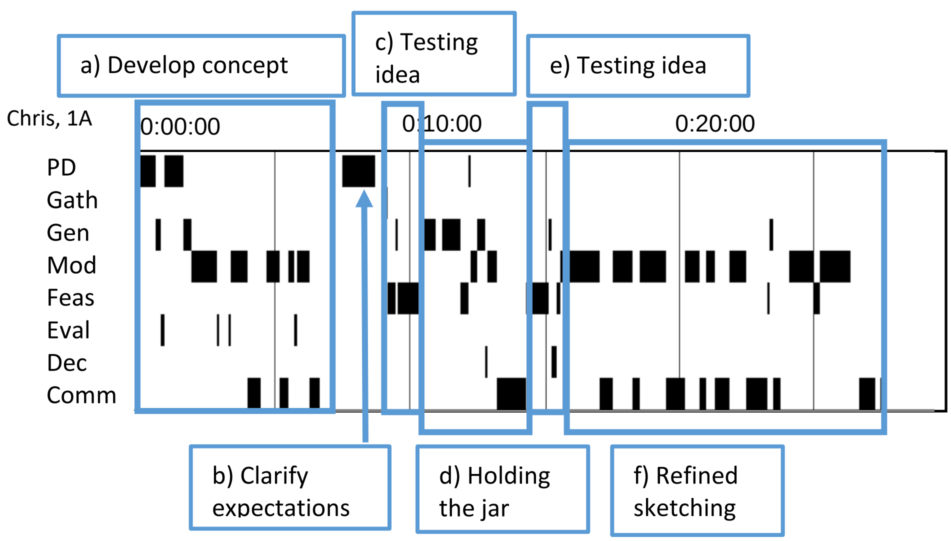


Figure 24 Overview of design process, 1A interview with Chris

Figure 24 shows the timeline of Chris' design process in the 1A interview. Overall, he only spent 1% of his time in each of gathering information, evaluation, and decision-making, and 8% generating ideas. Chris only demonstrated two of the indicators of informed design behaviour summarized in Figure 15: creating detailed drawings and evaluating his solution against design goals. Overall, Chris' behaviour is consistent with someone demonstrating level three or level four, pre-reflective thinking where beliefs are defended as personal opinion (level three) or justified using idiosyncratic arguments (level four). Informed design behaviours such as generating a range of concepts, weighing benefits/trade-offs before making decisions, and revisiting design goals, were not present with Chris.

9.1.2 MJ

MJ has participated in several project-based learning environments including a high school IB class, the Shad Valley program, and a university design course the year prior to his interview. The university design course was fully online, and at a distance for MJ (he was in a different time zone, three hours behind), but the other experiences were in person. Shad Valley is an intensive, month-long program where students are mentored as they tackle a “wicked problem” in a theme identified by the organizers (for MJ, that was reducing waste generated by Canadians). Between the very open, ill-structured problem at Shad, the training and encouragement to generate multiple solutions before making decisions, and the social environment (working with, and around peers with mentors of various levels of experience present to provide feedback), Shad Valley does an excellent job building an epistemic climate that promotes personal epistemological development. MJ seems to have had more structured opportunities to develop his epistemology than most of the other participants (Oscar might be an exception).

In the design activity, MJ spent a significant amount of time brainstorming, coming up with 8 or 10 different ideas for how to open a jar single-handed before he refined his design criteria and started eliminating ideas from contention. MJ also delayed making any assumptions about the problem until after he had completed this early round of brainstorming. As MJ transitioned from the conceptual design phase to the more detailed design phase in the activity, he began to struggle, vocalizing that he felt he didn’t have the knowledge required to complete a sophisticated and detailed design of the device. MJ seemed to recognize the limits of his knowledge, seeking sources online to fill in some of the missing pieces (like the force required to open a jar and options for a mechanism to clamp on to the jar body), though he did struggle to find useful information in his online searches.

In the final, reflective section of the interview, MJ was able to vocalize more details for his design process than during the activity itself. He defined his design criteria, for example: to minimize complexity and cost, and maximize ease of use. When asked how he knew he made the “right” choice with his solution, MJ responded: “Well, there is no right solution”. He went on to say that the solution he chose seemed to optimize the criteria he had identified, and that is why he selected it. When asked to expand on how he would justify the design of his device to his boss, MJ attempted to convince his boss by describing the positive attributes of his device as he saw them, and as they related to his design criteria. Near the end of the final section of the interview, MJ recognized that this problem space was less open than the one he experienced in Shad Valley (which was more of a theme, and students had to identify their own problem).

One of his last comments in the interview was that he wished he had more knowledge so he could deliver a "better" solution. When asked what he meant by better, he commented that he meant "more complete" or more detailed. Throughout his behaviour in the activity, and in his comments during the reflective portion of the interview, MJ demonstrated mostly reflective thinking (level six). He didn't have the sophistication to justify his design choices objectively, but his choices of design criteria were reasonable given the provided context and he recognized that different choices could be made that would change the outcome.

Figure 25 shows the design process timeline for MJ's 1A interview. MJ spent 13% of his total time gathering information, 20% generating ideas, 4% in evaluation, and 2% in decision-making, and demonstrated all but one indicator of informed designers (MJ did not create detailed drawings/models of his solution). Examining MJ's behaviour generating a range of concepts, it is not possible to ascribe which aspect of MJ's prior training caused him to take that step to such an exaggerated degree compared to his peers. It is feasible that it was the procedural knowledge he received in Shad Valley that led to this effort. It is similarly feasible that MJ has achieved the reflective thinking level and so he understands that this is a crucial step in justifying decisions by weighing criteria.

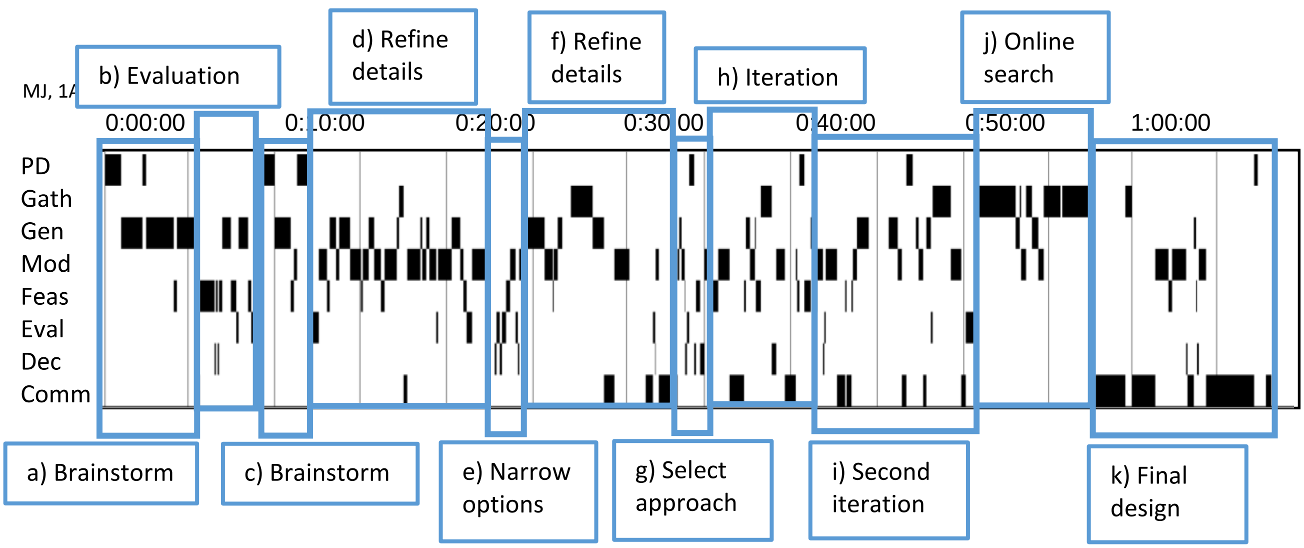


Figure 25 Overview of design process, 1A interview with MJ

9.1.3 Oscar

Oscar had several years of experience designing devices, particularly robotic devices, prior to enrolling at university. Oscar had taken part in four years of FIRST Robotics at his high school, completed a high school tech class where he learned CAD, had completed a high school coop placement in a hospital machine shop constructing patient lift devices, worked for an automotive parts supplier for a summer in 2019 designing an autonomous robot, and had joined the solar car design team at university prior to his interview. These opportunities were mostly unstructured, with limited instruction/mentorship, but they were highly complex, real-world environments that would be ripe with opportunities for generating epistemic doubt. The problem-solving environments that Oscar experienced were ill-structured and open-ended, and of significant duration (most of these experiences lasted several months). What is less clear about these environments is the degree to which Oscar engaged in resolution strategies. At a minimum, these experiences seem to have taught Oscar that design is not a domain where there is a single correct answer. When asked what he learned from his experience, Oscar commented: “It taught me not to be. I don't have to be perfect in everything I do. And no design is perfect. But iterating and making it better than the last time is what was…What was important to me.”

In the design activity, Oscar started by thinking about whether he wanted an electric or a manual device, and quickly went online to see what tools already exist to solve this problem. Oscar decided to avoid the electrical solution and stick with a manual powered tool because he personally prefers to not include electronic components unless necessary. Throughout his design activity, Oscar struggled with thinking aloud, and so he generally would work on the design with limited speech until prompted by the interviewer to keep talking and then he would review all the work he had recently completed. This makes it somewhat difficult to understand his decision-making process in detail, but his reasoning would frequently come out in the reviews of his work. In the later parts of the design process, Oscar generated a couple similar concepts, but his evaluation of each one was limited. In some cases, he relied on his personal experience with similar devices, but often it wasn’t clear why he selected one choice over the others. Oscar iterated with his design, refining it over time, but once the early choices had been made, he evaluated less and less, especially as he moved into selecting sub-components of the design. His overall approach of having a clamp hold a jar to a counter with a suction cup was consistent throughout and went unjustified.

In the debrief section of the interview, Oscar was able to recognize in hindsight a number of assumptions he made when solving the problem that were not stated explicitly while he was designing including the types of jars he was targeting and that he wanted a solution that was portable (i.e. quick and easy to store away when not in use). When asked how he knew he had found the right solution, Oscar thought he had a good solution that had fewer flaws than other designs, but he was not really able to elaborate on how he evaluated the differences. At the end of the debrief when asked what he would do differently next time, Oscar wished he had stayed at the beginning of the process a little longer and spent more time understanding the problem. Overall, he showed consistent quasi-reflective thinking throughout (level four). He recognized that there is uncertainty, and that no solution will be perfect, but his justifications were not grounded in evidence, they were idiosyncratic based on his intuition in the moment.

Figure 26 shows the design process timeline for Oscar's 1A design activity. Oscar spent 4% of his total time gathering information, 26% generating ideas, 2% evaluating, and 1% in decision-making, and demonstrated all the indicators of informed designers except for researching the problem space and weighing benefits/trade-offs before making decisions. Oscar is interesting in that he has more hands-on experience designing and building complex devices than any of the other participants, and he demonstrated most of the indicators of informed design behaviour, and yet his justifications for design choices were all very shallow in nature if they were given at all. Overall, Oscar seemed to have a less developed personal epistemology than some of the other students with less experience, but where their experience took place in environments with epistemic climates that were more conducive to personal development. It seemed that Oscar may have been lacking formal opportunities to engage in resolution strategies in his past experiences; many of his experiences were light on instruction and mentorship and likely did not have much explicit reflection occurring. It is feasible that Oscar has so far avoided thinking reflectively about his experiences that might have led to more development of his personal epistemology. This lack of development seemed to manifest in the over-reliance on intuitive, snap judgements that could not be explained after the fact.

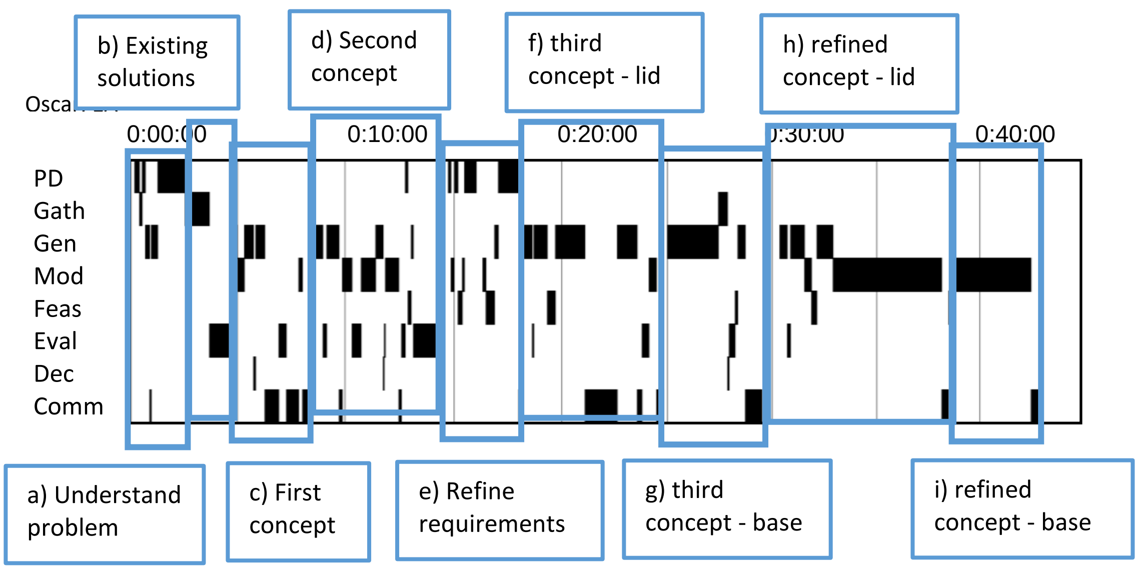


Figure 26 Overview of design process, 1A interview with Oscar

9.1.4 Patrick

Patrick's most relevant training comes from his wood-working hobby and his employment at a custom furniture maker. Patrick's wood-working skills were self-taught through watching YouTube and through completing projects for himself, which occasionally included 3D printed components. Assuming that he was watching more than one YouTube channel, Patrick was likely to have been exposed to a variety of solutions to the same problems which may have created epistemic doubt, but it is difficult to know to what degree

Patrick had epistemic volition or engaged in resolution strategies to develop his personal epistemology. Otherwise, Patrick had no organized training, no extracurricular programs, and no high school classes that he felt prepared him for design or engineering.

During the design activity, Patrick debated between two main concepts: something that replaces the user's missing arm versus something that is stationary and installed when needed. He also thought about different solutions to the sub-problem of holding the jar steady by thinking about different wood-working clamps that could be adapted to this purpose. Throughout the activity, cost was the main criteria that Patrick considered, though he never referred to it explicitly as such. He also thought briefly about how the user would store the device when not in use, but other design goals largely went unstated. Once his initial concept was finished, he began thinking about the experts he would want to talk to about his design (e.g. an expert on ergonomics, an expert on manufacturing). Patrick completed some evaluation of feasibility and cost, but little else. He similarly did some refinement of the shape/design of his device as he learned about manufacturing methods, but no real iteration on the concept. In the post-activity reflection, Patrick recognized the problem was open-ended and missing information with more than one solution, and some other alternatives came to mind as he talked (like an electric solution). When asked how he knew he had found the right solution to the problem, Patrick responded with: "I don't. I don't think it's necessarily like a right or wrong type thing. I just think it's more optimal." In follow-up questions, Patrick expanded on the pros and cons of the two clamp styles that he had identified in the design activity. Patrick was able to identify one main assumption he made to deal with the missing information in the design prompt; he made some assumptions around the physical capabilities of the disabled user. Overall, Patrick's justifications for his design choices did not have much depth; he felt the concept he selected was the simplest and cheapest to make. Patrick made some further justification based on the wording of the question: "And it's OK for them to require their own force because… I was told was that… They all need to open it with one hand. I guess. I don't know if I have missing information, but it didn't say that they couldn't, uh, use their rib I guess, or use their arm." When asked what he would do differently in a future design activity like this, Patrick recognized in hindsight that he wished he had thought about a broader range of solutions (outside of just wood-working tools). From Patrick's comments in the debrief portion of the interview, it seems like he is operating at a quasi-reflective level (likely level four, though there was some evidence of level five). Patrick still relies on comments from perceived authorities, but he recognized that knowledge is uncertain and was capable of making some justifications for his choices; they were just lacking in depth.

Figure 27 shows an overview of Patrick's design process timeline. Patrick spent 33% of his overall time gathering information (the bulk of which was spent researching manufacturing methods), 22% generating ideas, 15% of his time in evaluation, and 3% in decision-making. Patrick demonstrated three of the indicators of informed designers (researching the solution space, generating a range of concepts, and revisiting design goals) and two more in a limited fashion (stating explicit design goals and evaluating the solution against the design goals). Patrick has not had the benefit of many structured opportunities to develop his personal epistemology, though whether through his woodworking, or perhaps his extra years (Patrick is older than all of the other participants by two or three years), he has developed further than some of the other participants like Chris. This seemed to manifest in Patrick's efforts to come up with more than one solution concept, including for sub-problems in his solution, and in his willingness to seek out information that might help him develop his solution.

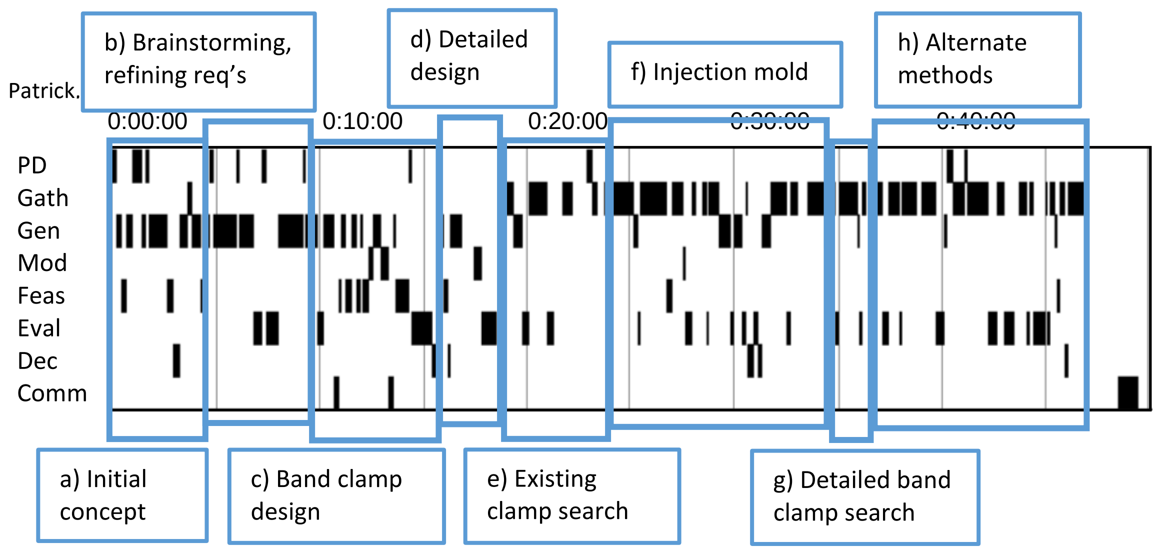


Figure 27 Overview of design process, 1A interview with Patrick

9.1.5 Michelle

Michelle has taken part in two activities that could have contributed to her personal epistemological development: the Technovation program, and the online hackathons during high school. Technovation was an in-person experience that ran for approximately three months where mentors gave instruction on topics like user interface design, app development, and developing a business plan before the students developed an app of their own design. The software development was mostly completed using an online website, so little actual programming was done; however, an open project-based learning environment with in-person access to peers and mentors is likely to create an epistemic climate that develops participants' personal epistemologies. Michelle has also taken part in several online hackathons in teams with her peers. The online nature of these likely limited some of the social development of her personal epistemology – the online environment could be expected to reduce the presence of social-based resolution strategies and reciprocal causation – however, epistemic doubt was likely. At the time of the interview, Michelle had also benefited from several weeks of instruction in ME 100.

In the design activity, Michelle talked about alternatives for powering her device early on, including a plug-in device, a mechanical device, or a battery powered device. She made a quick decision that plugging something in is inconvenient and so went with the battery powered device that she thought would be simpler than a mechanical one. From there, Michelle went online, found an existing solution that she liked, and she proceeded with that idea as the core of her solution. After the initial decision of the power source, Michelle did not conduct much evaluation of her solution, though she did try to evaluate the faults of the existing solution when she first saw it. Later in the process, Michelle also evaluated the reliability of the website she was reading (deciding it wasn't very reliable even though the information was relatively innocuous). In the reflection portion of the interview, Michelle recognized there were very few constraints in the problem as written, and she wished that more specifications were provided to her by the problem. Her main design considerations were limited and included little outside of what was given by the prompt. When asked, Michelle was able to recognize most of the decisions she made, but even in reflection, she didn't think about alternatives to the choices she made in her own solution. From the activity and the debrief after the activity, Michelle seemed to be employing mostly pre-reflective thinking. At several points in the interview, she looked to authority (e.g. the company specified in the problem statement) as the arbiter of what was important, or of what she should focus on. She seemed to occasionally stretch up to level 4 (quasi-reflective thinking), for example when she decided on her initial approach to the problem where she quickly evaluated three different approaches to the problem. When she was subsequently asked if she made the right choice, she wasn't sure that she had, but she felt the path she took was the easier device to design. When asked if she used anything from ME 100, she admitted that she did not think about criteria at all, only the constraints given by the problem statement (that it had to open jars using one hand).

Figure 28 shows Michelle's design process timeline. Michelle spent 14% of her total time gathering information, 17% generating ideas, 5% in evaluation, and 4% in decision making. Michelle demonstrated two indicators of informed designers during her process (researching the solution space and evaluating the solution against design goals), and three indicators in a more limited fashion (stating explicit design goals, researching problem space, and generating a range of concepts). Similarly to Jill, beyond the initial brainstorming of solution concepts and the online search for existing solutions, Michelle did very little concept generation, or evaluation of ideas before making a decision. Overall, Michelle and Jill demonstrated less developed personal epistemologies than was expected based on their past experiences, which were quite similar. With Jill, the impact of the Science Olympiad may have been lessened over time (she took part in it in grade 10), whereas with Michelle, perhaps the fact that Technovation was a software design environment lessened its impact in this mechanical design environment (which could also be true of the hackathon experiences for both Jill and Michelle).

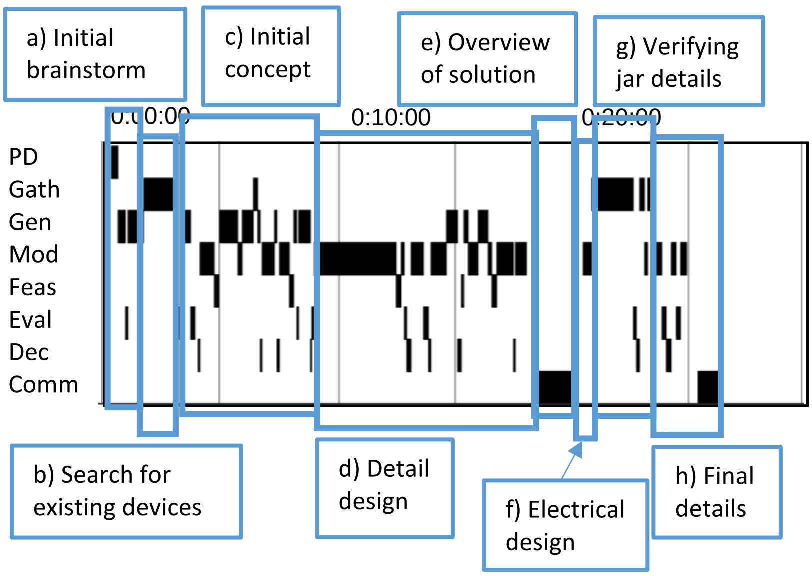


Figure 28 Overview of design process, 1A interview with Michelle

9.1.6 Cross-Case Analysis

Table 48 shows a summary of the stage of personal epistemological development exhibited by each student participant using King and Kitchener (1994), sorted by pre-university knowledge level. This table also summarizes the number of informed designer behaviours they exhibited in the 1A design activity, for example, Jay demonstrated four indicators in total, though two were demonstrated in a limited way. The students exhibited a range of development with two participants showing largely pre-reflective thinking (Chris and Michelle), the majority of participants showing quasi-reflective thinking (Jay, Jill, Patrick, Bond, and Oscar), and one student showing reflective thinking (MJ). As posited by King and Kitchener (1994), people often function within a range of stages, and in portions of the interview, some of the participants showed thinking of higher stages. Bond and Jill, for instance, exhibited pre-reflective thinking in some of the earlier phases of the design process when they were developing their overall solution concept, but reverted to quasi-reflective thinking when working on the detailed design of their solution. It is possible that as students faced higher cognitive loads – or insufficient knowledge – that they are not able to maintain reflective thinking, though MJ described a point late in his process where he wished he had more knowledge that related to mechanical engineering design, and yet he didn't retreat to earlier stages of personal epistemology in the same way as some of the others. It is possible that something in MJ's history better prepared him to face these moments of missing knowledge; perhaps his additional procedural knowledge was enough to carry him through these challenging moments. This finding is partially reinforced by Bond's design activity as well; early in the design process when he was able to use the design process taught to him in the Shad Valley program, he was able to maintain a higher stage of personal epistemology, but as he reached the later, more uncertain, portions of the design process, he retreated.

Table 48 Summary of personal epistemological development of each student participant, 1A

Prior Knowledge	Student Participant	Stage of Development (King & Kitchener, 1994)	# of indicators of informed design behaviour
Limited relevant knowledge	Chris	Level 3-4	2 total: 2 + 0 limited
Relevant factual/conceptual; limited procedural knowledge	Jay	Level 4-5	4 total: 2 + 2 limited
	Jill	Level 4-6	6 total: 5 + 1 limited
	Patrick	Level 4-5	5 total: 3 + 2 limited
Relevant procedural knowledge	Michelle	Level 3-4	5 total: 2 + 3 limited
	Bond	Level 4-6	7 total: 5 + 2 limited
	MJ	Level 6	7 total: 7 + 0 limited
	Oscar	Level 4	6 total: 5 + 1 limited

Figure 29 shows an overview of the indicators of informed designers from Crismond and Adams (2012), sorted by the level of personal epistemological development from King and Kitchener (1994) that the student participants demonstrated in the 1A interview. From this figure, some patterns emerge: researching the problem space was demonstrated mostly by students who were level five or higher, generating a range of concepts/ideas was demonstrated mostly by students of level four or higher, weighing benefits/trade-offs before making decisions was only demonstrated by a student of level six, revisiting/re-evaluating design goals was only demonstrated by students of level four or higher. Michelle was somewhat of an outlier here in that she demonstrated some research of the problem space, and stating explicit design goals (albeit to a more limited degree), even though her epistemological development seemed to be in the level three to four range based on the debrief after the design activity. Other indicators of informed designers did not seem to be strongly connected to personal epistemological development as they were demonstrated by a wide cross-section of the student participants. This includes researching the solution space (demonstrated by seven out of eight students), creating detailed drawings/models (demonstrated by students from level three to level five or six), and evaluating solutions against design goals (demonstrated by seven out of eight students to at least some degree).

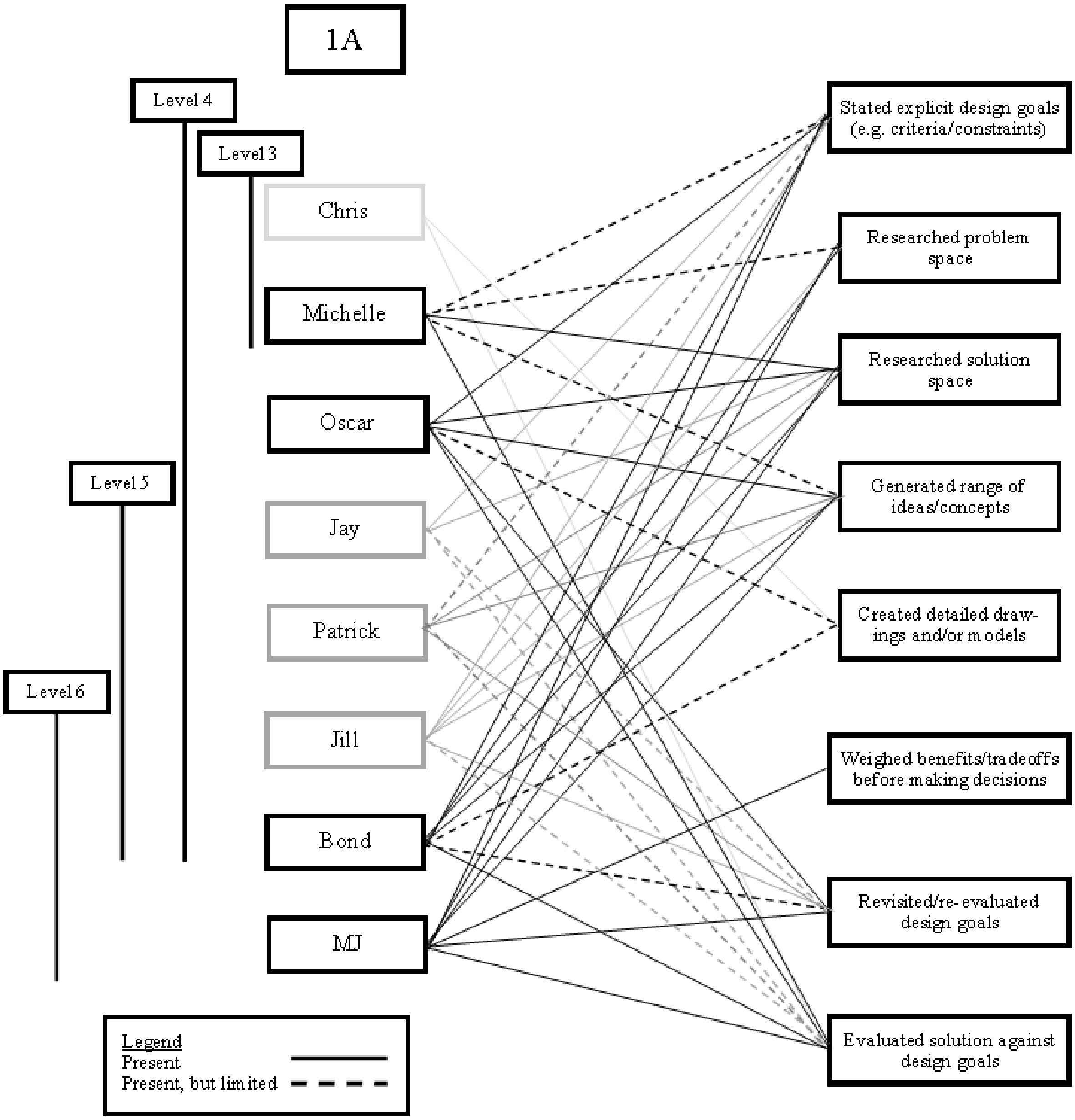


Figure 29 Indicators of informed design behaviours, sorted by level of personal epistemological development, 1A interview

Table 49 Percent of time spent in each design step during 1A interviews, sorted by personal epistemological development

Design Phase	Chris	Michelle	Oscar	Jay	Patrick	Jill	Bond	MJ
Personal Epistemology	**3-4**	**3-4**	**4**	**4-5**	**4-5**	**4-6**	**4-6**	**6**
Problem Definition	10%	1%	8%	9%	4%	15%	12%	6%
Gather Information	1%	14%	4%	17%	33%	12%	8%	13%
Generate Ideas	8%	17%	26%	12%	22%	14%	13%	20%
Model	37%	38%	29%	26%	2%	38%	19%	23%
Feasibility Analysis	10%	3%	4%	16%	5%	3%	6%	7%
Evaluation	1%	5%	10%	10%	15%	5%	2%	4%
Decision	1%	4%	0.4%	2%	3%	1%	1%	2%
Communication	23%	10%	14%	8%	3%	10%	23%	18%
Transitions (mean=83)	50	62	75	64	112	40	112	148

Table 49 summarizes the time spent by each student in each phase of the design process, sorted by personal epistemological development. In the 1A data there are no obvious trends in the step(s) in the design process where students at different levels of development spent more time.

9.2 Conditions for Epistemological Development – First Year Design Course

To understand the possibilities of personal epistemological development provided by the first-year design course (ME 100), Rule and Bendixen's (2010) Integrative Model of personal epistemological development was used to deductively analyse the ME 100 instructor interviews. These interviews were coded using the main components of the Integrative Model: conditions for creating epistemic doubt, evidence of student epistemic volition, resolution strategies, and the environment provided in the course including the epistemic climate of the course and opportunities for reciprocal causation. More detail on the analysis method can be found in section 4.2.5. This section will only briefly describe the activities being discussed, for a more complete picture of the teaching and learning activities in the course, they are summarized in section 7.1.

9.2.1 Design, Communication and Professionalism

When asked how he describes engineering design to 1A students, the DCAP instructor explained: "engineering design is justified decision making", and it is "going to involve trade-offs of one thing versus another". In subsequent answers in the interview, it seems that by "justified", the instructor meant through some form of quantitative analysis; this could take the form of analytic modelling, simulation, or calculation, or through experimentation with and/or validation of prototypes. The instructor emphasized to students that design is iterative; that the designer's understanding of both the problem and the solution will evolve over time as ideas are tested and improved. In addition to describing the uncertainty involved in understanding and attempting to solve design problems, the DCAP instructor also showed students multiple representations of the design process before largely focussing on one in the course. In this way, the instructor showed the uncertainty present in procedural knowledge in engineering design, something that was likely unusual for students. The epistemic climate in ME 100 is in stark contrast to the other courses in the semester which are presented with much more certainty; questions in algebra, calculus, or physics will have a single correct answer, and frequently have a specific, correct process that students are meant to follow to reach the answer. When talking about the views of students as they enter his course and his general approach with the course, he said: "they [the students] come in very much thinking that it [engineering design] is objective. That there is a right answer… if I can at least get them to the point of, there are multiple better and worse answers, I've done a lot."

From the instructor's description, it seems that there were opportunities for creating epistemic doubt during lectures, but the experiential activities appear to be the primary location where Rule and Bendixen's "mechanisms of change" (viz. epistemic doubt, epistemic volition, and resolution strategies) are enacted in the course. The DCAP instructor brought up three activities that are relevant to this discussion: the pill crusher case study, the paper rocket activity, and the toy project. In the pill crusher case study, a different design process is used compared to the other activities in the term. This is an instructor-led design exercise where students are led through the process of designing a mechanical device that can crush pills for elderly patients. This case study gives the instructor an opportunity to demonstrate their personal epistemology, and what is expected of "justified decision-making" in engineering more broadly. In the paper rocket activity, students are given an hour to construct a paper rocket that will get launched by pressurized air. During this activity, the students are designing their projectiles (mostly rocket shaped, but some not) surrounded by their peers solving the same problem. This gives them an opportunity to see that the problem has more than one solution. The instructor also discusses the design of the launching system, giving some details on the iterations in creating it. In past years the instructor has conducted a debrief session with the students after the paper rocket activity to help them see how it fits with the design process, but that did not happen in fall 2021 due to the timing of the activity and related lectures. These two activities could have provided more opportunities for students to implement resolution strategies through structured reflections; however, they did include social interaction with the instructor (both activities) and with their peers (the rocket activity).

While the mechanisms of change were present to a smaller extent in the paper rocket and pill crusher activity, they were included in more significant ways in the toy design project. This project was very open in the description of the problem; students could design any toy they like, as long as it met the technical requirements for the course. This openness is uncommon outside of design courses and is fruitful ground for creating epistemic doubt in students. In the first half of the term, the instructor led a divergent thinking exercise to help the students in developing their project ideas. These ideas were then summarized and submitted to the teaching team and the students received feedback on the feasibility and fit for the course. In the second half of the term, the students developed prototypes, presented them to the teaching team and to the industry partners, received feedback (on both their prototype and on their project constraints and criteria), and then refined the prototypes for the final demonstration day. Throughout, the students had many decisions to make as they constructed their prototypes, and were expected to seek out help, or research their solutions independently to meet the project deadlines. Throughout the project, the instructor emphasized that their prototypes did not need to function well (or at all) at the symposium to receive full grades on the project. The final assessment was a written report where the students had to give the justifications for the decisions they made and describe the process they followed. This project includes all three mechanisms of change: the openness of both the problem and solution space create epistemic doubt, the students need to independently develop prototypes and document their thinking providing them with epistemic volition, and the deliverables (presentations, demonstrations, and the report) provide resolution strategies of various types (social interaction in presentations and feedback rounds, reflection and retrospective review in the final report).

The DCAP instructor emphasized throughout the interview that ME 100 is very different from many other courses in the mechanical engineering curriculum, and likely quite different from student pre-university experiences, in that: "there isn't a right answer to how do you design this. There's better and worse". Throughout the course, the instructor emphasizes that mechanical engineering design is full of uncertainty, but that choices will need to be made in forming a solution and an engineer needs to be ready to justify those decisions. In this way, the instructor is building an epistemic climate that is conducive to developing student personal epistemology. The epistemic knowledge representations, epistemic instructions, and the instructor's personal epistemology reinforce this climate throughout the course's teaching and learning activities. There were limits to this, however. The instructor discussed the logistical challenges of this course: there are two sections of 100-120 students being taught simultaneously, and it is challenging to find both a physical space and time in the course to construct an environment that is conducive to reciprocal causation. There were limited opportunities where students interact with their peers as they were confronting epistemic doubt, and similarly limited opportunities where they interact with the teaching team; and these were mostly centered around the toy project. This was certainly made more difficult due to the Covid-19 pandemic restrictions that were in effect that limited the number of students who could be in a room at the same time to half the class.

One element that seemed to be missing from the course was a meta-cognitive component for the students. Students were expected to conduct research, build prototypes, and meet project deliverable deadlines in the course, but it is not clear if they were monitoring their own thinking as they did these tasks. For example, as they researched potential solutions, how were they evaluating the information they were finding? Were they monitoring their design process in the toy design project, or just working to deadlines? The course was consistent in constructing an epistemic climate conducive to developing student epistemological beliefs. The core of the toy design project does an excellent job of creating epistemic doubt, and the students clearly have volition – no one will do the project and the report for them –

however, there was limited social interaction between peers during the project limiting the opportunities for reciprocal causation, and elements like meta-cognition were more implicit, than explicit.

9.2.2 Engineering Graphics and Design

As with the DCAP side of the course, EGAD set up an epistemic climate that is conducive to developing student personal epistemology. Where DCAP emphasized the analytic justification of design decisions, EGAD strove to have students think about the "art of design". The EGAD instructor achieved this in a few different ways during the semester: the instructor emphasized creativity and divergent thinking (which DCAP did to a certain extent as well); professional practice of historically significant professional designers were discussed each week with the "designer of the week"; and the instructor reiterated to students that they needed to consider both the functional and aesthetic side of design in the solutions they create. In EGAD, the instructor commented that he is trying to show students a different side of the discipline and was trying to give them a break from the heavy analytic portions of the term with a more creative/artistic experience. Throughout the instructional parts of EGAD (there are not lectures in EGAD per se, it is a three-hour lab that goes back and forth between instruction/demonstration and students practicing the skills of technical communication and CAD), the instructor was building a similar epistemic climate as in DCAP, but from a different and complimentary perspective.

EGAD has much less formal instruction time than DCAP does, and so student learning happens most through hands-on practice of the skills being taught. Relevant to this discussion, there were four case studies/mini projects during the term that were conducive to generating epistemic doubt in students: designing a backrest for a canoe seat, re-designing and improving a hoist, designing a laser cut snowflake, and designing a 3D printed cell phone stand. These four activities had more structure, were less open, and were shorter in duration than similar activities in DCAP as EGAD only represents 40% of ME 100 (and is three hours per week instead of six). The emphasis in these activities (including the emphasis in the assessment) was not so much on design or design process but was more focussed on the communication and CAD skills that students were demonstrating in the activity. The EGAD instructor sees the course as being pivotal for preparing students for their first work term and so the emphasis is on building the CAD skills they will need in their work terms. Of the four projects, the canoe seat, re-designing the hoist, and designing the snowflake are all completed in a single session and so are one or two hours long. The phone stand was spread across three weeks of the term, and so students spent more time refining their designs and had more opportunities to receive feedback. All 4 projects were open enough to create epistemic doubt and as they were all individual assignments, the students had the epistemic volition during the design process. They had to make judgements and decisions to complete their solutions. From the conversation with the EGAD instructor, it seems like only the phone stand project had a reflection assignment at the end, the rest were just submitted for grading by the course TAs. Resolution strategies were thus more limited in EGAD than in DCAP.

EGAD takes a different approach from DCAP in relation to team versus individual work. The EGAD instructor intentionally structured his side of the course as only individual assignments. He wanted to ensure individuals were given the opportunity to form their own ideas and complete their own work without being overly influence by others. The EGAD instructor was particularly concerned with students being intimidated by their peers. Unlike most of the other engineering skills students will obtain at university, CAD skills are not uncommon pre-university. Even within the eight students in this study, Oscar had years of experience with 3D modelling including competing at the provincial level in a skills challenge for CAD. The unfortunate side effect of this policy is that students don't benefit as much from learning from each other. Reciprocal causation was limited to interactions between students and the teaching team. As with DCAP, EGAD similarly does not include much explicit practice of meta-cognition in the course.

9.2.3 Preliminary Analysis of Epistemic Climate in ME 100

Overall, the two parts of ME 100 (EGAD and DCAP) create an epistemic climate that is conducive to developing student personal epistemology. Both instructors demonstrate their personal epistemologies and include epistemic instructions in both their lectures and in their experiential activities. Both parts of the course have multiple activities/projects that would conceivably create epistemic doubt in students. The toy project is the most significant of these, both due to the duration of the project and due to the openness of the problem space, but the other activities in the term are also sufficiently open-ended to create opportunities for students to question their beliefs about knowledge, engineering, and design. Students also have sufficient autonomy to make their own decisions as they develop their solutions to provide them with epistemic volition. Many of the activities include explicit resolution strategies like reflective assignments, summary presentations to receive feedback, or reports; however, DCAP does this more than EGAD. Reciprocal causation was more limited in both EGAD and DCAP for several reasons including the logistics of the large enrollment and classroom environments, the pandemic restrictions, and the course design (especially in EGAD) to ensure individuals develop the necessary skills. Meta-cognition was also limited in both parts of ME 100. It does not seem like it was discussed or demonstrated by either instructor; there were limited live demonstrations of design/problem-solving skills in the term where this skill could be demonstrated. The reflective assignments and reports did not seem to require students to think meta-cognitively. This could be an area of improvement for future course offerings.

The next section will examine evidence of personal epistemological development from the student participants in their 1B interview. In some cases, this will enable a further examination of the impacts of ME 100 on their development, but other pertinent experiences will also be discussed.

9.3 Preliminary Analysis of Personal Epistemological Development – 1B

This section will present data and analyses of the 1B student interviews to investigate **RQ1** (What effects do knowledge and personal epistemology have on novice designers' design behaviours) and **RQ2** (What impact does one semester of design instruction have on novice designers' knowledge, personal epistemology, and design behaviours). Similar to section 9.1, the data will be drawn from all three sections of the student interviews. The first third of the interview investigated what the students remember of ME 100 as well as other activities that they took part in prior to the 1B interview; this could include competitions (like hackathons), work within a student design team, a co-op work term, or other relevant activities. Details of the design activity and debrief will be discussed where student behaviours/comments reveal aspects of their thinking and/or personal epistemological development. As with section 9.1, King and Kitchener (1994) is the model used to understand student personal epistemological development. Jill and Jay's detailed descriptions and analyses can be found in Appendix H.

9.3.1 Michelle

When asked about any open-ended projects in her 1A term, Michelle could only think of the toy project. Michelle felt that the overall goal of the project (to make an entertaining toy) was clear, but she realized that their group had to set several smaller goals to help them navigate what their toy would do, and how it would do those things. Michelle's work on the project related mostly to the mechanism that would open/expand their small collectible once it landed on the ground, as well as writing the report. When asked about the role of the teaching team in the project, Michelle described them as like guardrails to make sure the group stayed on schedule. Michelle described spending time walking through the symposium, she was interested to see what all the other groups designed for their project and described seeing some interesting projects. Reflecting on the entire project, Michelle felt it taught her to start a design process without a solution in mind, and to focus on the problem first. From Michelle's description, she was less involved in the design and build parts of the project – which would have limited her epistemic doubt – however, taking ownership of the report (which is the primary means of reflecting on the project during the course) may have given her additional opportunity for taking epistemic volition and for engaging in resolution strategies. Michelle's deliberate exploration of her peers' designs at the symposium also would have contributed to reciprocal causation. Overall, the project provided Michelle with an epistemic climate conducive to developing her personal epistemology.

Michelle also remembered some of the other design activities in the 1A term including the coffee maker dissection and the cell phone stand. She distinctly remembered the process of discussing criteria and constraints in relation to both the coffee maker activity and the toy project, and like with the toy project symposium, Michelle extended some effort to see what her peers created for their cell phone stands. Michelle also joined the formula motorsports team in 1A but confessed that she was too busy with schoolwork to really contribute to the team. Lastly, Michelle was an 8-Stream student, and so did not have a work term before her 1B interview.

During the design activity, Michelle thought of some constraints and criteria for her solution as she worked to identify what was meant by a stuck double hung window. Michelle seemed to get a little hung up on the wording of the problem statement and it seemed to push her towards a portable device that could help someone open a stuck window (as opposed to something that is installed permanently on the window). Throughout the design activity, Michelle would come up with several different approaches to solving the problem/sub-problem she was concerned with at the time. For example, she thought about two large families of solutions: approaches that apply a force to the window to get it moving, and approaches which would clear the window tracks of debris to ease movement of the window sash. Ultimately, she settled on a device which would vibrate the window to get it moving, and once her concept was decided, she again paused to think of several mechanisms for accomplishing this sort of vibratory force. Michelle conducted some research on potentially useful mechanisms at this stage, but her online searches were not very fruitful. There were some decisions in the second half of the activity where Michelle made some snap judgements – perhaps as she fatigued – for example, when deciding on what would encase her solution, Michelle commented: “It could be a plastic box, I'm thinking, that has the motor inside. So because plastic is everywhere and it works. So that's fine. So it would. It would be a plastic box with a hole in it.” Mostly though, Michelle continued to think of alternatives throughout her process like how it would attach to the windowsill (adhesive, suction cups, screws), or when deciding on the material of the arm that connects to the window sash. Michelle was also considering multiple criteria when talking about material selections (e.g. strength of material first, then weight, then cost). Interestingly, Michelle was perhaps the only student with a measurable, objective constraint (she wanted her device to work on 80% of windows), and she spent time near the end thinking about how she would conduct the tests to verify this constraint.

In the post-activity debrief, Michelle recognized there was missing information in the problem statement, and she turned to assumptions to navigate this uncertainty (e.g. she made an assumption that the user was concerned with the vertical sliding of the window sashes, and not the tilting feature common in modern double-hung windows). Michelle commented that she wished some of the criteria were spelled out in more detail in the problem statement, like the desired weight or cost of the device. When asked to clarify why she assumed the problem was concerned with the vertical sliding motion of the windows, Michelle commented that she made that assumption because she understood how that mechanism worked, and that she didn't have any experience with the tilting mechanism. Michelle described similar reasoning for going with a mechanical solution and not a chemical cleaner/lubrication solution like Jill: "I picked like the mechanical one, because I think you can solve it other ways too. Like you can definitely do a chemical thing that clears their tracks for you, but I I don't know about that as much", though she provided more nuanced rationale later in the debrief portion of the interview. Michelle also described her process for optimizing for functionality above the device weight or cost because of how the question was worded, and though this could be her relying on the judgement of an expert to decide what's important, it is also conceivable that Michelle desired a conversation with the end user to better understand their priorities. When asked to justify her design to her boss, Michelle wanted a report where she had the space and time to describe the decisions in detail, including the testing that (presumably) would validate her decisions (like for strength of materials, etc). Michelle seemed to recognize that the report would act as a sort of argument for the design as she created it. Michelle also seemed to have knowledge of how a report like this would be structured, including describing the business plan for the device. This knowledge may have come from ME 100, though no other participants had any comments resembling Michelles, or perhaps this was drawn from experience in the Technovation program in high school. Overall, Michelle showed sophisticated thinking in not only generating multiple options, but in her layered criteria for selecting an option to pursue, though there were also times where Michelle excluded concepts because of her interpretation of the problem statement wording (which was perhaps acting as an "expert" of sorts to Michelle). It is challenging to place Michelle's comments in King and Kitchener's model as there was evidence of quasi-reflective thinking (level four) in her idiosyncratic arguments for parts of the design like the plastic housing around her solution, as well as evidence of reflective thinking (level six) in her criteria-based approach to selecting design options.

Figure 30 shows Michelle's design process timeline in 1B. Michelle spent 17% of her total time gathering information, 20% of her time generating ideas, 7% evaluating, and 4% of her time making decisions, which are similar to her 1A design process where she spent 14% of her time gathering information, 17% generating ideas, 5% evaluating, and 4% making decisions. It is important to note that Michelle spent 3 times as long designing in 1B compared to 1A. In the 1B design activity, Michelle all but one indicator of informed designers (all except for creating detailed drawings/models) a significant improvement from 1A where she only demonstrated two fully (research solution space, evaluate solution against goals), and three partially (define design goals, researching problem space, and generating a range of ideas).

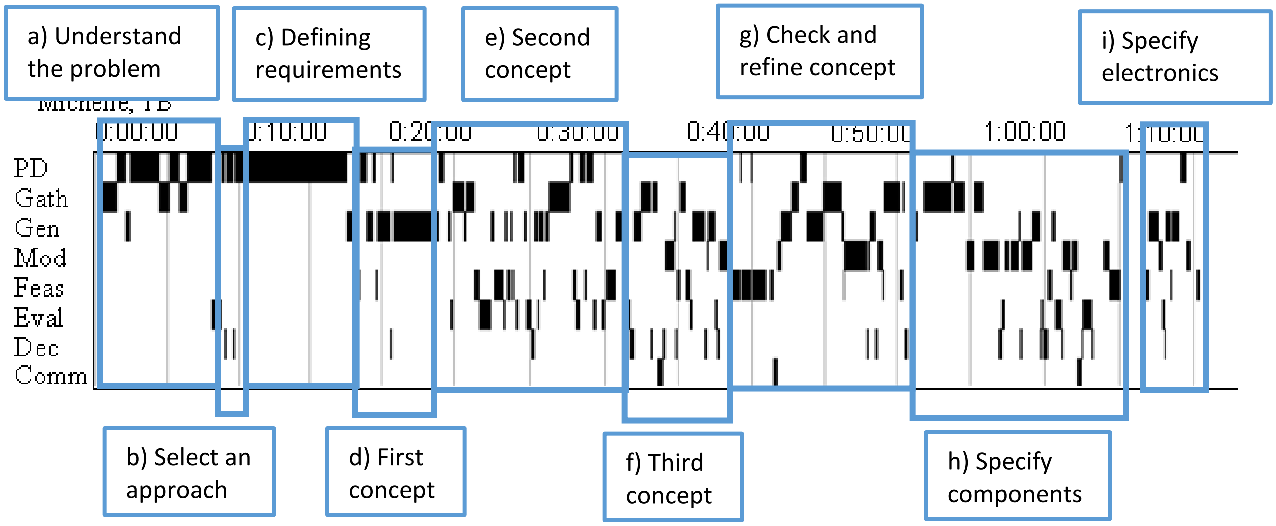


Figure 30 Overview of design process, 1B interview with Michelle

The significant increases in both the number of indicators of informed design behaviour and in the level of personal epistemology that Michelle exhibited in 1B are quite remarkable and are challenging to explain as development does not usually happen this quickly, though several possibilities exist. In her 1A interview, Michelle seemed to under-perform compared to her peers when considering her level of pre-university design experience, it is possible that there was something "holding back" her performance. This could have been fatigue, or perhaps Michelle was distracted in the 1A interview (Michelle's interview took place on the Saturday of Thanksgiving weekend, and the start of reading week). It is also possible that something in her 1A experience "unlocked" a level of performance that she was not capable of in her 1A interview. This second option is somewhat less likely as she had the benefit of a full month of instruction in her 1A term before her interview (though the toy design project had not progressed very far at that point in the term).

9.3.2 Patrick

Patrick felt that ME 100 was the only course that taught design in 1A, and the toy project was the only open-ended assessment he could remember. Unlike many of the other participants, Patrick could see the disconnect between projects which would make a good toy and projects which would earn the most grades in the course. He perceived that the instructions, assessments, and the advice his group were given by the teaching team were aimed at ensuring their success in the course and not necessarily with producing the best toy prototype they could. Patrick remembered learning about constraints and criteria, the PRIMED design process taught in DCAP, and especially the design instruction in EGAD. In his toy project, Patrick talked about having multiple concepts for the toy prototype that his group decided between. In general, he seemed to be describing some of the indicators of informed designers in how his group made their decisions on the toy project (including setting design goals, generating a range of concepts, weighing benefits and trade-offs, and evaluating the solution against the design goals), though it seemed that they frequently set design goals to optimize their performance in the course. Patrick couldn't remember any other projects where design was taught in 1A, though he remembered the cell phone stand when he was asked. In Patrick's case, he printed the cell phone stand on his home 3D printer and so was able to make an iteration on the design when the first prototype was unstable. Patrick did not participate in any engineering extra-curricular activities in his 1A term as he was playing for the varsity hockey team, though he did mention continuing to design and 3D print parts/pieces for his home woodshop, especially over the holiday break between terms. From the conversation with Patrick, it seems that he struggled to balance playing varsity sports with returning to school after three years and being successful in his various courses. These challenges on his time, and the way he described the toy project, it seems that there was limited epistemic volition to improve his personal epistemological development, though there were still likely opportunities for both epistemic doubt and resolution strategies in how the course was implemented.

Patrick began his design activity by thinking broadly about the causes of the window sticking. After searching online, he recognized there were three components that could stick (viz. the lock, the tilting mechanism, and the vertical sliding mechanism), but chose to ignore the lock to focus on the main window mechanisms. His original idea for solving the problem was to stop the window tracks from getting dirty in the first place. He thought of the different kinds/sources of debris that could end up in the window tracks, and thought of some mechanisms that can remove that debris as it accumulates over time. About halfway through his design activity, Patrick checked his ideas against the problem statement and chose to pivot to a device which could apply a force to a window to help the user open it, instead of trying to stop it from sticking in the first place. With this new problem frame, Patrick came up with a few different concepts to apply a force to the window sash including using wedges or a prybar with the handle on the window, and a linear actuator that could help move the window sash once it was partially open. Ultimately his choices came down to two options: a pry bar and an electric actuator. He felt the prybar would work better with a fully closed window, and so that is the option he pursued. Patrick realized he may have to make assumptions about the physical ability of the user(s) so that he could continue developing the solution. Near the end of the design activity, Patrick had some similar comments to his 1A activity where he seemed to view some decisions as outside of his control, or to be made by others, but that type of thinking was much less common in his 1B interview than in 1A. Throughout this portion of the design activity, Patrick seemed to struggle with how to choose between his various concepts. Using structured decision-making tools at this point may have helped him with the uncertainties of how to proceed and may have helped him use his time more efficiently as well, but he didn't seem to use any of the tools taught in ME 100. Unlike many of his peers, the first mention of criteria didn't happen until about 78 minutes into the design activity and was only mentioned briefly in passing. At the 80-minute mark, Patrick finally settled on a concept he was happy with, which meant he had to rush to finish the design in the 90-minute design activity, ultimately leaving some details unfinished (like how to help the user operate the upper sash).

In the debrief portion of the interview, Patrick recognized that there was more than one way to solve the problem, and that he tried to apply what he learned in ME 100 by slowing down and thinking about the problem before jumping into a solution. He felt that sketching and spending time defining the problem were the main lessons he was able to learn in 1A and apply during this interview. When asked about the process he used, Patrick admitted he was relying on his intuition, and so didn't rely on the structured process taught in ME 100, which he seemed to indicate was a sign of less skill on his part: "it depends on if you think there's like a right process. Like… a better engineer would have written out criteria, constraints, whatever, Like ME 100. I kind of went more intuitive." Near the end of the debrief, Patrick also commented that he will be looking for engineers at his co-op work term placements to show him the right process to use when solving design problems.

In a later question, when asked how he knew he had found the right answer to the problem, he confessed that he didn't know it was necessarily the right solution. He recognized that it depends on the assumption of physical ability that the designer makes of the user. Patrick clearly remembered the questions asked in the debrief from the 1A interview, commenting: "I remember you asked me before in the last one… how can you justify saying that they have to apply some force with like holding the jar or whatever, so it's like they say I'm just thinking of that today like I don't know if I can justify it, but I have to make an assumption somewhere to come up with a solution." Very few, if any of the other participants seemed to make such a strong connection to the discussion in the 1A interview, but Patrick admitted that part of the reason he took part in this study was because he thought it would be good for his development. When asked what decisions he can remember making, Patrick focussed on the decisions about the problem frame (e.g. the decision to focus on helping someone open a stuck window over avoiding the problem of sticking); he couldn't really identify decisions he made about his prybar solution, perhaps due to the limited time spent on developing it. Patrick was self-aware of his process; that he spent most of his time on the problem, and comparatively little on the solution. When asked how he would justify the choice to go with a prybar-style solution, Patrick based the decision partly on his estimated cost and complexity of the device versus the linear actuator-based alternative, and partly on his perception of the efficacy of the solution with a fully closed window (he felt the prybar would work better in this scenario), though he confessed the concerns about cost and complexity may be seen mostly in hindsight; they weren't explicit while he was designing.

He also didn't feel he had the knowledge to design the linear actuator solution. Generally, Patrick seems to be demonstrating level five, quasi-reflective thinking in most of the activity – his beliefs/justifications are context dependent (like with his comments on the assumed physical ability of the user) – however, when he was commenting on his procedural knowledge and making decisions on how to structure his process, he seemed to regress to pre-reflective thinking (level three) where he would like an expert to show him what process he was meant to use to solve the problem.

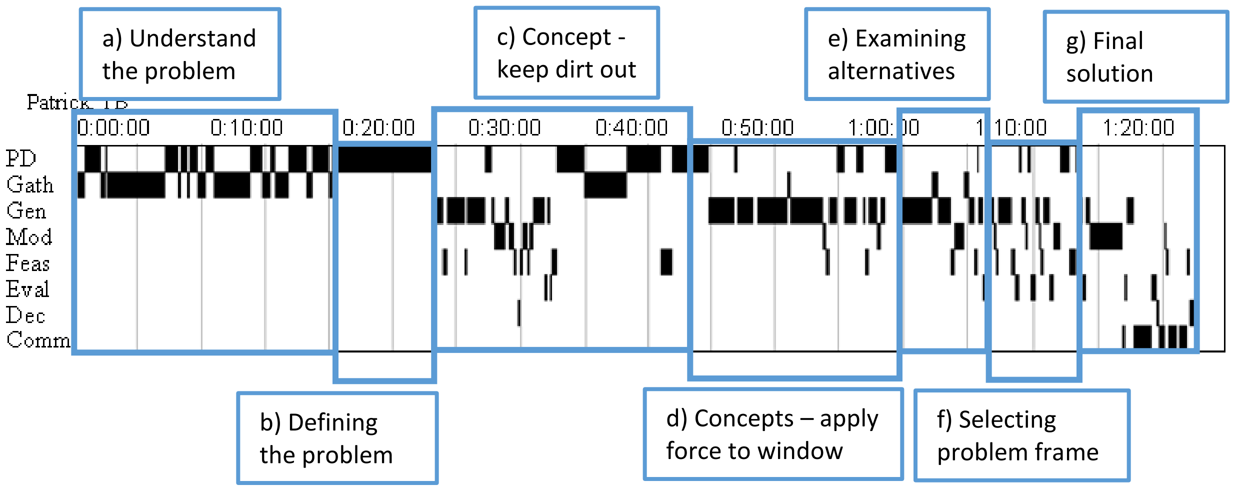


Figure 31 Overview of design process, 1B interview with Patrick

Figure 31 shows the timeline of Patrick's design process in the 1B interview. Overall, he spent 19% of his time gathering information (focussed on the problem space), 27% of his time generating ideas, 3% evaluating, and 1% in decision-making. In 1B, Patrick demonstrated four indicators of informed designers (researching the problem space, generating a range of concepts, weigh benefits/trade-offs, and evaluating the solution against design goals) and two in a more limited fashion (stating explicit goals, and revisiting design goals). This is a slight improvement from 1A where he demonstrated three fully (researching solution space, generating range of ideas, and revisiting goals), and two to a lesser extent (evaluating solution against goals, and stating explicit goals). Patrick spent such a long time understanding the problem and thinking about how to prevent the window from sticking, that he rushed through the development of his final solution to the problem. With more time, or a more balanced approach between problem and solution space, Patrick may have demonstrated more indicators (like researching the solution space).

9.3.3 Chris

Thinking about his 1A term, Chris recognized that ME 100's toy project was open-ended, especially when compared to the other assignments and projects that he worked on that term. Chris remembered the process that ME 100 led them through during the project, and in particular, the concepts of constraints and criteria seemed to have stuck with Chris. When asked about any disagreements he or his team had with the teaching team during the toy project, he didn't remember disagreeing with anything they said, though he admitted their advice did lead to some adjustments in what they were building. Chris also admitted he wasn't that involved in the design and construction of their toy, so perhaps his teammates might recall these conversations differently. When asked how they knew their toy was successful, Chris admitted the prototype didn't achieve all the goals they set out for it, but otherwise did not describe other metrics for defining success in the project. When asked about the rest of the term, he didn't remember any other projects or design activities except for the cell phone stand. When asked how he decided which concept to pursue for his phone stand, Chris admitted that he used a very subjective evaluation of the appearance of his concepts and picked one he liked the look of.

Chris' other experiences prior to the 1B interview consisted of manufacturing parts for an automotive student design team based on the designs of other people. Chris described the plans as detailed and accurate, requiring few or no changes as he manufactured the components. Chris' work term was as a general laborer in an automotive assembly plant where he was given clear instructions of what he was expected to do, and he repeated those tasks throughout the term. Overall, the only environment which seems to have an epistemic climate conducive to developing his personal epistemology was in ME 100 in 1A, though by allowing his teammates to do most of the design and construction of the toy prototype, he may have limited the chances of creating epistemic doubt, thereby limiting his development.

During the design activity, Chris confronted the openness of the problem statement early on; recognizing that he would need to make some assumptions to navigate the missing information in the prompt. For Chris, this manifested in two assumptions: deciding what physical ability the user would have, and what "stuck" meant in the context of the window. As he was deciding on the first assumption, Chris asked the interviewer to describe the physical ability of the user (and was told to simply do what he must to solve the problem), ultimately deciding to assume the user only had the use of one hand/arm. For the definition of "stuck", Chris chose an assumption that he felt made the problem easier to solve. He didn't want to research all the ways a window could get stuck, and so he decided to design a device that would allow a user to unlatch the lower window sash with only one hand. Neither assumption was justified, compared against alternative interpretations, or re-evaluated as his process continued. While designing, Chris tried to follow the process taught to him in ME 100, and overall, he was able to operationalize that knowledge fairly well, developing problem constraints early on in the process. During both the design activity and the post-activity debrief, Chris recognized the openness in the problem statement and was cognizant of his approach of using simplifying assumptions as a way of navigating the openness. In the post-activity debrief, when asked how Chris will decide which process to employ in future design problems (that taught in ME 100 or the one he was learning in ME 101), Chris was not able to provide a strong justification for using one over the other, commenting: “the fundamentals are the same, right? Like, it's not crazy different they might use like some different terminology here and there or they might put like one step before the other… Or I guess like, I'll just do whichever one's easier for me if, like, they are that different.” Chris also had a difficult time describing any trade-offs he can recognize in his design – Chris only reflected that the aesthetics were sacrificed for functionality. When asked how he would justify his design to his boss, Chris gave a similar answer as in 1A; he tested the operation in his mind and felt it would work, and it was a simple design with few moving parts.

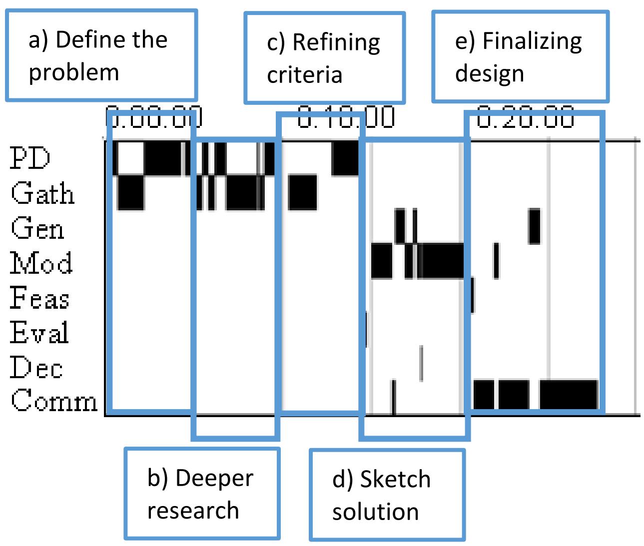


Figure 32 Overview of design process, 1B interview with Chris

Figure 32 shows the timeline of Chris’ design process in the 1B interview. Overall, he spent 22% of his total time gathering information (mostly on the operation and construction of double hung windows), 5% of his time generating ideas, 1% evaluating concepts, and no time in decision-making. Chris demonstrated three indicators of informed designers (stating explicit design goals, researching the problem space, and creating detailed drawings/models), and one to a limited degree (evaluating solution against design goals); two more than in 1A where he did not state design goals or research the problem space. Overall, Chris’ behaviour is consistent with someone demonstrating mostly level three, pre-reflective thinking, where beliefs are defended as personal opinion, showing limited to no growth since the 1A interview.

9.3.4 Oscar

When asked about his 1A term, Oscar commented that the toy project was “extremely open-ended”; later commenting that it was too open-ended, and he didn’t enjoy the process. Oscar described it being difficult for his group to decide what to do, but that they used a combination of group brainstorming and online research to help reduce the uncertainty with the project. When asked about the role of the course teaching team, Oscar felt they were helpful in the conceptual stage, and with determining their project's criteria and constraints, but were less involved after that point in the project. Like Patrick, Oscar commented that the project has less emphasis on the mechanical/physical prototyping, and instead was mostly focussed on the final report. When asked how his group knew they had solved the problem, Oscar commented "Honestly, we didn't. Uh, the problem was whatever we designed it to be, so in some ways there was kind of no answers to it. It was kind of what we felt was an adequate solution." Oscar did not think any of the other 1A courses taught him design, though he mentioned that he enjoyed the EGAD portion of ME 100, especially the practical design tips and anecdotes from the instructor. When asked about other activities in ME 100 that taught design, Oscar mentioned the paper rocket and coffee machine activities – two activities that were rarely mentioned by the other participants – but he still felt there was not much design practice in 1A. When discussing the formal design process taught in ME 100, Oscar commented that the use of criteria and constraints were heavily enforced in the toy project, but that he struggled with determining measurable goals that were grounded in evidence: "We just kind of were like maybe threw out a number for like the supposed max weight of the product or something like that. The max height of it. It was something that frustrated me a little bit about the project structure in general. Was that like, how are we supposed to have constraints or criteria when it's not well defined what we're doing in the first place?" Oscar seems to be commenting that the effort of writing criteria and constraints did not serve his group as a way of reducing uncertainty in the project. Oscar also mentioned that the project timeline was so short that they couldn't iterate on prototypes; once they had one that worked, they had no time to improve it, they just had to push forward. When asked about the cell phone stand, Oscar remembered the process as: ideate several concepts for the stand, and the teaching team would tell you which was the most feasible one to build. Near the end of the first section of the 1B interview, Oscar commented that he likes doing projects for himself where he can do whatever he wants and can make decisions in the moment. He understood engineers can't operate this way in the real world, but he finds projects for himself more fun than the formality of the design process used in ME 100. Oscar had no other extra-curriculars or side projects in the fall term, he said he just needed to focus on his coursework. Overall, Oscar did not seem to face many circumstances in 1A where he had epistemic doubt; the situations where there was uncertainty that had to be resolved just seemed to be difficult for him, and not very enjoyable.

Oscar's work term was at a makerspace on Waterloo's campus. When asked what the main takeaways from the term were, Oscar commented that it was to always be learning, and to be willing to learn. During the term, he was assigned projects where he had to quickly learn the programming language to contribute to the development of the project. He felt he had a lot of independence in the work environment but could approach the staff if he had questions; and he appreciated the makerspace staff asking (and respecting) the opinions of the coop students on purchasing/operational decisions. In addition to his work in the makerspace, Oscar also continued work on the design and manufacture of a 3D printed/laser cut Antikythera mechanism that he started researching in high school. Overall, while there were several experiences of relevance to mechanical engineering design during the work term that no doubt contributed to Oscar's knowledge and skills, there seemed to be few opportunities to generate epistemic doubt.

From the start of the design activity, it was clear Oscar had more experience with this style of window than many of the other participants; and, unlike some of the others (like Jay and Patrick), Oscar wanted to make sure his solution helped with the operation of both window sashes. After a brief search online to verify he understood the window style, Oscar jumped into creating criteria and constraints. His constraints were obvious items like setting a target ceiling on the price ($100), that it needed to fit any size window, and had to help with both window sashes; and his criteria were that it be simple and intuitive to use. He then listed a bunch of solution concepts including mechanisms that could be useful to applying a force to the window like screws, levers, and hydraulics, as well as other concepts like applying a quick shock to the window, as well as sillier ideas like explosives to shake it loose (this was reminiscent in some ways of MJ's divergent thinking process from the 1A interview). Again, unlike the other participants, Oscar also thought about different parts of the window that a device could attach to when applying an external force. As he thought about solution concepts, Oscar added additional criteria like the solution shouldn't block the view out the window. As Oscar outlined some quick pros and cons of each solution idea, he mentioned other criteria (like ease of storage and ease of mounting) that he seemed to think were relevant to that solution, but he didn't formally add these other considerations to his list initial list. Oscar quickly decided that the crowbar was worth pursuing in more detail based on its ease of storage. Later on, after evaluating it against the problem statement, he decided it "actually wasn't the best solution" but didn't elaborate on why not. He next pursued a hydraulic design, because, as he said: "it would be fun" to design. He found a reference design for a car jack online that he drew inspiration from. After completing most of his design sketch, Oscar talked about what he would like to do next: "So… what I usually like doing is trying to make a prototype where I… if this was like real life, I would probably print something or make something that would be a very rough estimate of one of these. And then I evaluate from there and then I'd go back. I guess at this point in my career… I just like kind of going back and forth quickly. I'm a somewhat impulsive guy in that kind of sense." Oscar ended up designing two solutions (a crowbar and a jack) that were independent of one another but worked at different points in the window's travel (the crowbar would get the window started and the jack would work once the window was partially open). However, in his movement through the process, Oscar forgot about the upper window sash – early on, he checked his concepts against his design goals, but ultimately, he did not do the same for his solution(s) and missed one of his initial constraints.

In the debrief portion of the interview, Oscar recognized that his process was similar to the one that was taught in ME 100, and that there was more than one approach to solving the problem. When asked how he knew he had found the right solution, Oscar commented: "I didn't. I'd say once again this… The concept of the right solution has never really set well with me. I don't think there is a correct solution to everything…There are some more feasible solutions, but just because something's less feasible doesn't mean that it's in incorrect… Like I think the only thing that would make a solution incorrect as if it doesn't fit the criteria or the constraints." The comment is interesting in that he didn't explicitly check his solutions against his constraints, and didn't use his criteria to weigh the benefits/trade-offs of his various solution concepts. Oscar seems to recognize what he should do, but when he was designing, he didn't take these steps. When asked if he was prioritizing any of his criteria, he commented that intuitiveness/ease of use was the most important one. When asked why he chose the prybar solution, Oscar mentioned additional criteria that he didn't bring up during the design activity (viz. durability and mechanical simplicity). When asked to about the trade-offs of his design, Oscar struggled to name much; he commented that the hydraulic solution is more complex than some of his other concepts but is more efficient. Oscar is an interesting case; he has more experience than most, if not all the other participants, but it doesn't seem to have prepared him for open-ended problems. He was annoyed with the openness of the toy project, and he relies strongly on his intuition to make judgements, even when he is trying to apply a structured process to his thinking. Further, his justifications are quite idiosyncratic, shifting over time as his views on the best concept change. Oscar seemed to be mostly operating in quasi-reflective thinking level four, extending to level five at times.

Figure 33 shows the timeline of Oscar's design process in the 1B interview. Oscar spent 21% of his time gathering information, 7% generating ideas, 2% evaluating, and 0% in decision-making. In 1B, Oscar demonstrated all the indicators of informed designers, though several were demonstrated in a more limited way (creating detailed drawings/models, weighing benefits/trade-offs, revisiting design goals, and evaluating solution against design goals). This is similar to his 1A interview in most respects; in 1A he didn't weigh benefits/trade-offs or research the problem space and only created detailed drawings in a limited way; showing little improvement from his experiences in 1A and his first work term. Overall, Oscar struggled to put into practice the procedural knowledge that he was taught in ME 100, rushing his decisions and making intuitive judgements on ever-shifting criteria. It's hard to know what to attribute this to, it could be an issue with energy or motivation – Oscar commented near the end of the interview that "today was that especially not creative day" – or perhaps he has picked up some "bad habits" of design. At the end of the debrief conversation, Oscar was asked why assumptions are necessary in design, and he responded: "Because we don't know everything... I know for engineers sometimes like… you don't need to know exactly how much something is gonna weigh. You just need to know if it's gonna weigh over a certain amount and past that point, who cares? … like I think it's good to make assumptions because like you don't need it to be super precise all the time." In any case, Oscar seems to have little epistemic volition to change his ways of thinking and could be avoiding epistemic doubt by getting frustrated and disengaging.

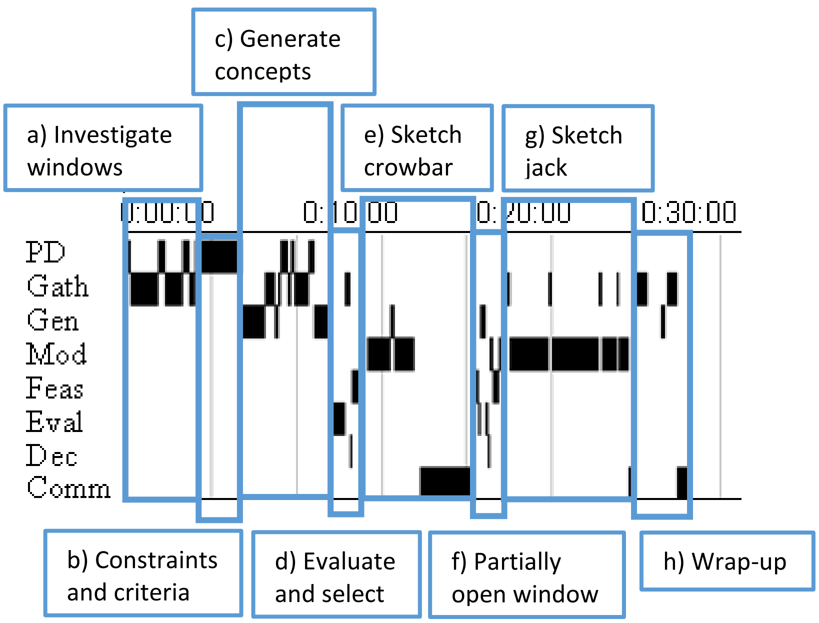


Figure 33 Overview of design process, 1B interview with Oscar

9.3.5 MJ

MJ remembered the toy project from ME 100. His group were able to outline the functions they wanted their toy to do, but they didn't know how to execute their ideas with the physical prototype. Their main strategy to resolve the unknowns in the project was through a process of trial and error of different approaches, as well as seek help from peers – both in their program, and in other programs. MJ described being very active in the early ideation process for their toy, slightly less involved in the technical decision-making, but involved in the prototyping and building because he was only one of two group members in Waterloo that term. MJ described the interaction with the teaching team as providing them approval for their idea early in the process and then backing away, though MJ did get help from the DCAP instructor when they ran into issues with getting their prototype working. MJ felt that EGAD was where he learned the most in 1A; SolidWorks and AutoCAD ended up being important for his work term, and he felt that DCAP was more theoretical and less practical. MJ couldn't remember other specific instances/activities that were design practice in 1A, but the methods for idea generation seemed to stick with him. MJ also commented that he still preferred the process taught in Shad Valley over the one taught in ME 100. When asked how his toy project group knew they had found the right solution, MJ commented: "I don't know if we did. I think the closest we did get was when a TA would say that looks like it's feasible or possible. And that's that was it pretty much external validation was the only time we knew for sure and the rest of the time I think we were just Winging it." When asked a follow-up about whether MJ ever disagreed with advice from the teaching team, he felt he didn't have enough knowledge/experience to disagree with them. MJ felt the toy project taught him to slow down and think things through before jumping in to trying to solve the problem. MJ did not take part in any other design teams or groups in 1A as he was worried about his time management and his ability to pass his courses, though he did take on a side project to learn Python and experiment with a Raspberry Pi during 1A and his work term.

MJ's work term was with a consulting company that designs and manufactures custom solutions for external clients. His work with the company was mostly manufacturing and assembly, but he also updated drawings with changes described by his boss and was given the opportunity to design simple components. MJ felt the main things he learned were testing, manufacturing/assembly skills, CAD, and electronics. MJ described his boss as very supportive, frequently giving him opportunities to learn new things by being a little ambiguous with his requests so MJ would need to do some independent learning. When asked if he had any situations where MJ disagreed with his boss or co-workers, MJ was very firm in his answer that he would not disagree with his boss, though he would point out mistakes if he saw them. This is similar to how MJ described his interactions with the ME 100 teaching team: he didn't feel he had the expertise required to argue with the advice he was given. MJ felt that EGAD prepared him well for his work term, and that the work term taught him many best practices. Overall, the work term seemed to support his learning, but opportunities for epistemic doubt were perhaps limited.

In the design activity, MJ started by thinking through a range of disabilities that a user might have, and that his solution might need to accommodate. MJ opted to use the language of ME 101 (i.e. functional and non-functional requirements instead of criteria and constraints) to describe his design goals and went back and forth between thinking of solution concepts and refining his requirements. In the debrief, MJ mentioned that he has an easier time using "requirements" over "criteria and constraints". MJ thought of three main concept solutions: a pry bar, a jack-style device, and pulleys which pull up the window; he also thought of a couple options for connecting the device to the windowpane/sash, and for mechanisms for the user to interact with the device. MJ decided he would like to accommodate people in a seated position like wheelchair users, and so ruled out some solutions. As with many of the other participants, MJ didn't fully understand the operation of a double hung window and so focussed mainly on the lower window sash. As MJ selected the various components of his solution, like using a suction cup as the method of attachment to the windowpane, he typically did not communicate a justification for the choice, though he occasionally would mention one shortly after making the decision. After thinking through his first design, MJ revisited the problem statement to make sure he was still solving the problem set out for him and then came up with a couple more concepts for his solution. Ultimately MJ selected the first concept he came up with: a suction cup to attach to the window, and a screw mechanism to apply the upwards force. MJ spent some time thinking through the potential issues with this design, and realized he didn't really know how the internal mechanism would work for this style solution, but he kept working on it. About halfway through the activity, MJ felt he was not making forward progress, and he expressed a desire to talk with someone else to see what they think of his solution but ultimately kept going with his design. Throughout the activity, MJ would come up with multiple options for each component, and would sometimes mention the shortcomings of that concept, or would adjust his requirements as he narrowed his options. However, he did not really justify the choices or do any structured comparisons between options in the moment. Near the end of the activity, MJ went online to help write out numerical specifications for the strength of the suction cup, as well as some other features of his design like the target price, the weight, and strength of the device. He also continued to adjust his requirements by adding in that the device should also help close the window. MJ ended by describing his solution, and by laying out assumptions he made about the user.

At the start of the debrief, MJ commented that he has learned in design problems there are often unknowns that will remain unknown, and so assumptions are a crucial part of the engineer's toolkit to moving forwards with solutions to these problems. When asked how he would know that an assumption is reasonable, MJ struggled a bit to answer, but eventually said he would rely on external resources like research and advice from experts while paying attention to the problem context. MJ recognized that he bounced around between problem requirements and solution ideation, which is evident in the first half of the design timeline; and he implied that he felt this was not a good, or desirable way to go through the design process. MJ mentioned that his priorities for the design were for a solution that was small, simple, reusable, and that can be used by someone from a seated position. He was able to identify several trade-offs with his design including some concerns with the difficulty of installation if someone had limited use of their hands, as well as concerns about the cost because he was not sure what would go into the screw mechanism in his solution. MJ was asked to justify his choice to use a suction cup on the windowpane, and his response was that he felt it was the most user friendly to install and remove. Overall, MJ was consistent throughout the design activity and debrief with his design goals, his priorities, the choices he made, and the justifications; especially compared to some of the other participants like Oscar brought up new/different criteria when asked at different points in the interview. In the design activity, MJ seemed to be operating at level 6, reflective thinking; though there were times where he described a desire to have an authority weigh in on his ideas which may reflect a less developed personal epistemology. The tension between how he describes interactions with experts, and how he acts on his own is notable.

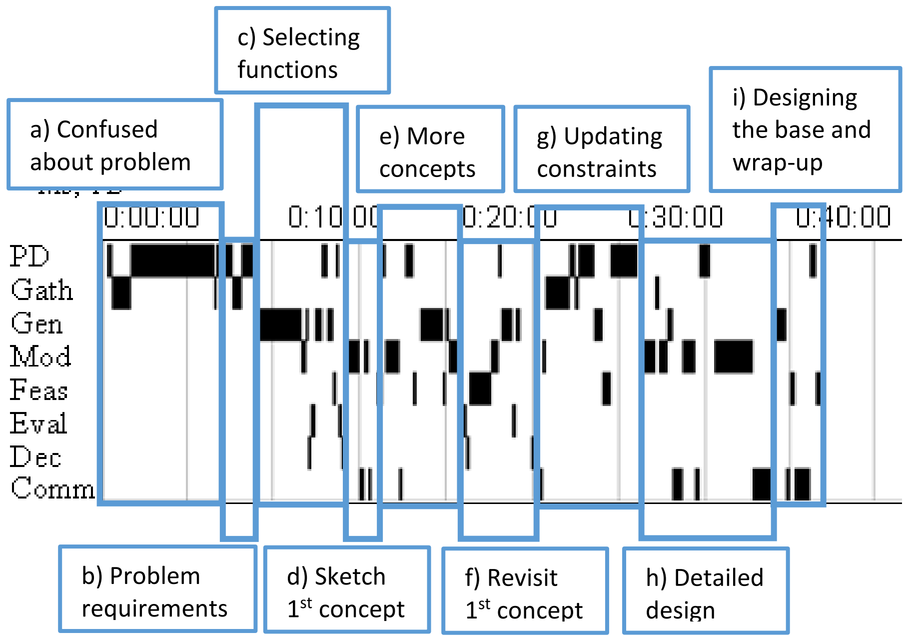


Figure 34 Overview of design process, 1B interview with MJ

Figure 34 shows MJ's design process timeline in 1B. MJ spent 8% of his time gathering information, 18% generating ideas, 2% evaluating, and 2% in decision-making. In 1B, he demonstrated all eight indicators of informed designers, but his drawings/models were limited in detail. This was a slight improvement over 1A where he didn't create detailed drawings at all. In the initial part of the interview when talking about the ME 100 teaching team, or his employer on work term, MJ described deferring to their authority and not asserting his own ideas. This could be viewed as a less developed personal epistemology where he is seeking to understand the truth from a perceived expert, and yet when he's in full control of the problem-solving situation, he shows higher level thinking and informed behaviours. It is possible that this is an issue with MJ's confidence in these situations, and/or perhaps an element of the imbalance of power perceived between the expert and MJ, especially given his history of needing to repeat the 1A term.

9.3.6 Cross-Case Analysis

Table 50 shows a summary of the stage of personal epistemological developed exhibited by each student participant using King and Kitchener (1994) in the 1B interview. The students are sorted into their respective academic stream to make it clear who participated in a work term (the 4-Stream students), and who did not (the 8-Stream students). The final column summarizes the number of informed design behaviours each student demonstrated, for example, Jill demonstrated five in total, but two were demonstrated in a limited way. Considering personal epistemological development first, many of the students showed a regression in their demonstrated stage of development. In some cases, this was a regression only in the high end of the range of stages they demonstrated (viz. Chris), in others this was a regression only in the low end of the range of stages they demonstrated (viz. Patrick), while others regressed across their entire demonstrated range (viz. Jill and Jay). Two of the students demonstrated more developed personal epistemologies in 1B compared to 1A, Oscar saw a one level increase in the upper end of the range of stages he demonstrated; and Michelle saw a significant increase across the entire range of stages demonstrated in her interview. MJ, who demonstrated the most developed personal epistemology in 1A did not show any change from his 1A to his 1B interview.

Table 50 Summary of personal epistemological development and indicators of informed design behaviour

Stream	Student participant	**1B** - Stage of development	**1A** - Stage of development	**1B** - Indicators of informed design behaviour	**1A** - Indicators of informed design behaviour
8-Stream	Jill	Level 3-4 -	Level 4-6	5 total: 3 + 2 limited -	6 total: 5 + 1 limited
	Patrick	Level 3-5 -	Level 4-5	6 total: 4 + 2 limited +	5 total: 3 + 2 limited
	Michelle	Level 4-6 +	Level 3-4	7 total: 7 + 0 limited +	5 total: 2 + 3 limited
4-Stream	Chris	Level 3 -	Level 3-4	4 total: 3 + 1 limited +	2 total: 2 + 0 limited
	Jay	Level 3-4 -	Level 4-5	4 total: 1 + 3 limited -	4 total: 2 + 2 limited
	MJ	Level 6	Level 6	8 total: 7 + 1 limited +	7 total: 7 + 0 limited
	Oscar	Level 4-5 +	Level 4	8 total: 4 + 4 limited +	6 total: 5 + 1 limited
+ indicates an improvement from 1A, - indicates a regression from 1A					

Examining the number of indicators of informed design behaviours demonstrated by each student in 1B shows an improvement in five out of seven students (viz. Patrick, Michelle, Chris, MJ, and Oscar), no change in one (viz. Jay), and a regression in one (viz. Jill). Examining their behaviours in more detail shows that while Jay demonstrated 4 indicators in both interviews, he appears to have regressed in 1B as he only demonstrated a single indicator fully (compared with two in 1A). Seeing the improvements in Michelle from 1A to 1B is even more pronounced when comparing against the rest of the participants – Michelle and Oscar are the only students to improve in both their personal epistemological development and in the number of informed design behaviours they demonstrated. As discussed in section 9.3.1, it is not clear what could have led to such a large increase as Michelle did not have the benefit of a work term prior to her 1B interview, and she participated in a more limited set of extra-curricular activities than many others.

Table 51 summarizes the time spent by each student in each phase of the design process in the 1B interview, sorted by personal epistemological development. Unlike in 1A, there are some observable differences in where students of different levels of development spent their time in the 1B activity. Students who demonstrated personal epistemologies (however briefly) of level five or higher generally spent a higher percentage of their time in decision-making and in generating ideas (Oscar is an exception here). Similarly, students who demonstrated personal epistemologies of level six or higher spent noticeably more time in decision-making and in feasibility analysis than their peers.

Table 51 Percent of time spent in each design step during 1B interviews, sorted by personal epistemological development

Design Phase	Chris 1B	Jay 1B	Jill 1B	Patrick 1B	Oscar 1B	Michelle 1B	MJ 1B
Personal Epistemology	**3**	**3-4**	**3-4**	**3-5**	**4-5**	**4-6**	**6**
Problem Definition	23%	19%	14%	32%	14%	23%	29%
Gather Information	22%	21%	20%	19%	21%	17%	8%
Generate Ideas	5%	7%	9%	27%	10%	20%	18%
Model	17%	21%	39%	8%	29%	11%	18%
Feasibility Analysis	1%	5%	6%	5%	4%	10%	8%
Evaluation	1%	2%	4%	3%	3%	7%	2%
Decision	0%	0%	0%	1%	0.5%	4%	2%
Communication	23%	18%	8%	4%	12%	1%	10%
Transitions (mean=70)	50	36	48	113	45	152	68

Figure 35 provides more detail on the indicators of informed design behaviours demonstrated by each participant. Comparing back to the 1A indicators summarized in Figure 29, there is an increase in the number of participants who researched the problem space (as discussed in Chapter 7, this was likely due to the students having little familiarity with the term “double-hung window”), and a noticeable increase in the number of participants who weighed benefits/trade-offs before making decisions. There was also a slight increase in the number of participants who created detailed models/drawings in 1B, while the rest were similar to the 1A interviews. It is interesting to note that the only participants to demonstrate the behaviours of weighing benefits/trade-offs before making decisions, and revisiting design goals, showed personal epistemological development of level five pre-reflective thinking or higher. This is a change from 1A where the only participant to weigh benefits/trade-offs before making decisions was MJ at level six, while Oscar at level four in 1A demonstrated revisiting design goals.

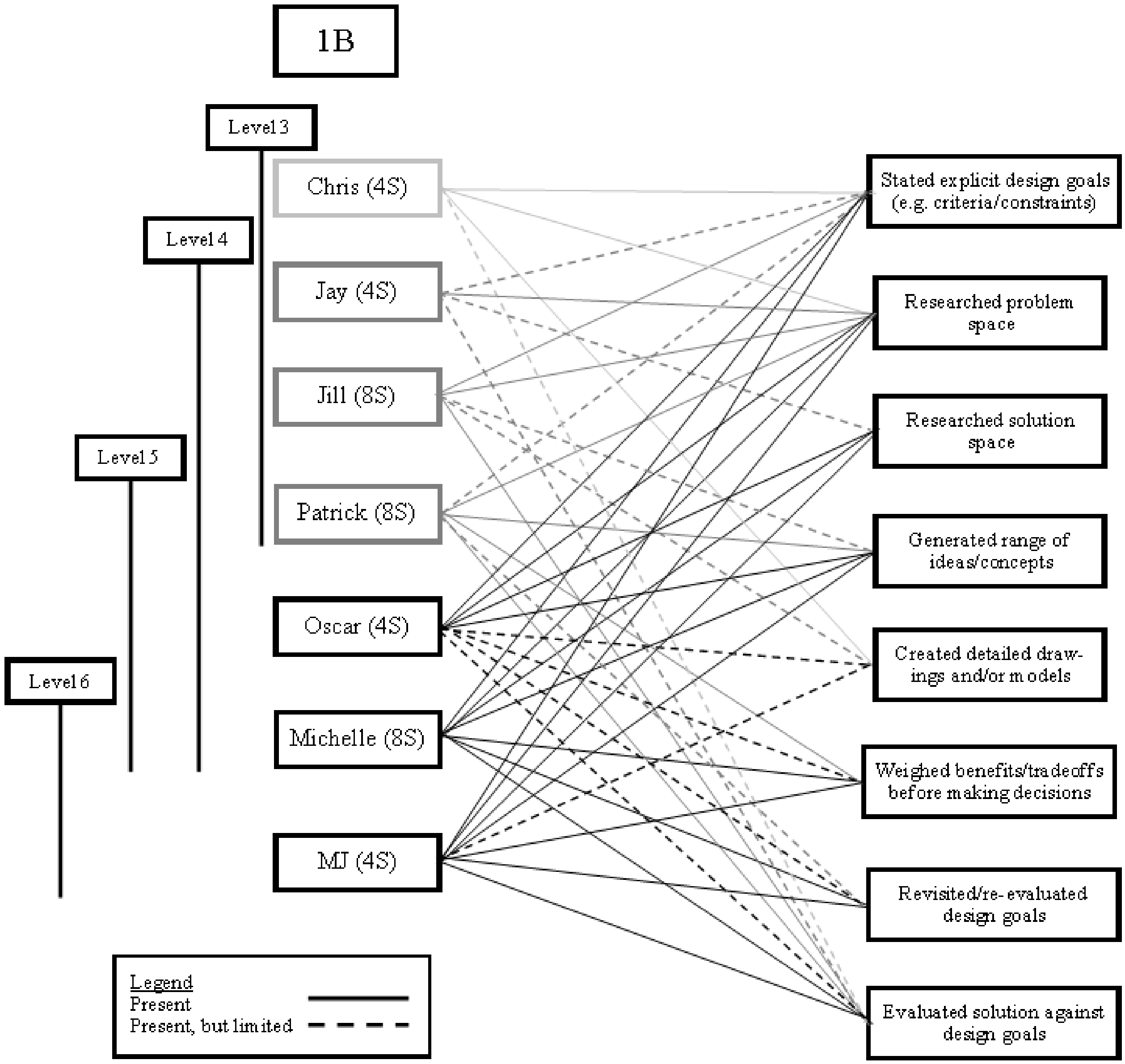


Figure 35 Indicators of informed design behaviours, sorted by personal epistemology, 1B interview (stream in brackets)

9.3.7 Other Observations

Power imbalances between student and superior may be interfering with accurate measurement of personal epistemology. The design activity in this thesis was posed as a work term setting where they were designing something for their employer, and in the debrief, they were asked to justify their choice(s) to their boss. For most students this wasn't an issue, however, some of the students seemed to react to the power imbalance in this setting. There were some similar comments made when asked if they disagreed with the teaching team in ME 100 during the toy project. A lack of self-confidence in these situations also came up in the interview. For example, Jay commented: "usually since I'm still like really inexperienced versus this person who's probably been in the industry for, like, my whole life, I would always sort of err on the side of them being correct. And then because there's probably some hidden thing that I haven't seen yet”. This comment seemed to reveal some elements of pre-reflective thinking in Jay (beliefs are justified because they agree with authority), but there may be other factors at play as well.

9.4 Summary of Findings

The following two sections will summarize findings from Chapter 9 that relate to **RQ1** (What effects do knowledge and personal epistemology have on novice designers’ design behaviours) and **RQ2** (What impact does one semester of design instruction have on novice designers’ knowledge, personal epistemology and design behaviours). This summary will focus on personal epistemology, a discussion on the interactions of knowledge and personal epistemology will follow in Chapter 10.

9.4.1 Effects of Personal Epistemology on Novice Designers’ Design Behaviours

Upon entering university, the majority of the student participants were exhibiting personal epistemologies of level four or five, quasi-reflective thinking stage, with three of the students demonstrating at least some attainment of reflective thinking during their interview (Jill, Bond, and MJ). From Table 48, in the 1A interviews, there was a general trend towards more indicators of informed design behaviour in students with more knowledge (especially with more procedural knowledge). There is also some evidence that when comparing students of similar knowledge levels (e.g. Jill and Patrick, or Jill and Michelle), students with higher demonstrated levels of personal epistemological development also seemed to demonstrate more indicators of informed design behaviour. Reiterating the patterns in Figure 29 that were identified in Section 9.1.6, researching the problem space was demonstrated mostly by students who were level five or higher, generating a range of concepts/ideas was demonstrated mostly by students level four or higher, weighing benefits/trade-offs before making decisions was only demonstrated by a student of level six, and revisiting/re-evaluating design goals was only demonstrated by students of level four or higher. Michelle was somewhat of an outlier here in that she demonstrated some research of the problem space and stating explicit design goals (albeit to a more limited degree), even though her epistemological development seemed to be in the level three to four range. Table 49 in Section 9.1.6, which summarized the time spent by each student in each phase of the design process, showed no obvious trends in where students at different levels of development spent more time during the design activity.

In the 1B interviews, as Table 50 shows, the general trend was for students with more relevant pre-university knowledge and a more developed personal epistemology to demonstrate more indicators of informed designers than students with less pre-university knowledge. It is challenging to separate the impact of personal epistemological development and level of pre-university knowledge in the 1B interviews. As seen in Figure 35, when sorting by level of personal epistemological development, the students ended up mostly sorted in order of pre-university experience, with the slight exception of Oscar who had the most pre-university experience but does not have the most advanced personal epistemology. Reiterating the findings from Figure 35 described in section 9.3.6, the only participants to demonstrate the behaviours of weighing benefits/trade-offs before making decisions, and revisiting design goals, showed personal epistemological development of level five pre-reflective thinking or higher. This is a change from 1A where the only participant to weigh benefits/trade-offs before making decisions was MJ at level six, while Oscar at level four in 1A demonstrated revisiting design goals. Across both the 1A and 1B interviews, the behaviour of weighing benefits/trade-offs before making decisions seems to be prevalent only in students who have developed their personal epistemological beliefs to at least level five. Table 51 in section 9.3.6 summarized the time spent by each student in each phase of the design process in the 1B interview and showed some observable differences in where students of different levels of development spent their time in the 1B activity. Students who demonstrated personal epistemologies of level five or higher generally spent a higher percentage of their time in decision-making and in generating ideas (Oscar is an exception here). Similarly, students who demonstrated personal epistemologies of level six or higher spent more time in decision-making and in feasibility analysis than their peers.

In the 1A interviews, Oscar, Jay, and Patrick all showed more sophistication in their thinking during the debrief after the activity than they did while designing. Jay, for example, was able to articulate his assumptions and criteria and constraints in hindsight during the debrief in his 1A interview, even though these were never mentioned during the live designing. The differences in thinking demonstrated by the students in 1B between the design activity and the debrief did not seem to be as large as in 1A.

9.4.2 Impact of One Semester of Design Instruction on Novice Designers' Personal Epistemology and Design Behaviours

After one semester at university (and one work term for the 4-Stream students), four of the seven student participants showed regressions in their personal epistemologies, one stayed the same, and two saw progressions. There did not seem to be any difference in development between 4- and 8-Stream students when examining their personal epistemology and design behaviours. Two out of three of the 8-Stream students regressed in 1B (only Michelle showed development in her personal epistemology), while in the 4-Stream group, Chris and Jay regressed, MJ stayed at a level six, and Oscar developed slightly by showing some indications of reaching level five. Only Michelle (8-Stream) and Oscar (4-Stream) improved their personal epistemology between the 1A and 1B interviews, and Michelle was an 8-stream student who did not have a work term prior to the 1B interview. However, the students with more pre-university experience began 1B demonstrating higher personal epistemologies than their peers. This meant improvements in personal epistemological development after 1A for the more experienced students (viz. Michelle and Oscar), and regressions in students with less pre-university experience (viz. Chris, Jay, Jill, and Patrick).

Even though most students appeared to regress in their personal epistemological development in the time between the 1A and 1B interviews, five of the seven students demonstrated more indicators of informed design behaviour. This would appear to indicate that at least some of the indicators of informed design behaviour are not strongly coupled to personal epistemological development. Stating explicit design goals, researching the problem space, creating detailed models, and weighing benefits and trade-offs were all demonstrated by more students in 1B than in 1A. Running counter to these indicators, there were fewer students who demonstrated research of the solution space, generating a range of concepts/ideas, and revisiting design goals in 1B. It appears that there could be a minimum level of epistemological development (or knowledge) needed before participants are likely to demonstrate some of these indicators; for example, as mentioned in the previous section, only students who showed personal epistemologies of at least level five demonstrated weighing benefits/trade-offs before making decisions. Since the students with more pre-university knowledge were also the students who demonstrated the most developed personal epistemologies in 1B, it is challenging to say with certainty whether these indicators are strongly tied to knowledge, epistemological development, or some combination of both.

10 Discussion and Summary of Findings

This exploratory case study has investigated how knowledge and personal epistemology impact novice design behaviours, at the beginning of mechanical engineering students' first two academic semesters. The following three research questions were investigated in this thesis:

> **RQ1**: What effect(s) do knowledge and personal epistemology have on novice designers' design behaviours?
>
> **RQ2**: What impact does one semester of design instruction have on novice designers' knowledge, personal epistemology, and design behaviours?
>
> > **RQ2.a**: What is the extent of this impact after one month? After five months?
>
> **RQ3**: What is the interaction between knowledge and personal epistemology while designing?

This chapter seeks to analyse and/or summarize the findings across the chapters (5-9) for each research question (as summarized in Figure 36), while also situating the findings in relation to existing literature. Chapters 5 through 9 presented data, analysis, and findings relevant to each individual section, with only limited analysis across different sections of this thesis. No new data will be presented in this chapter.

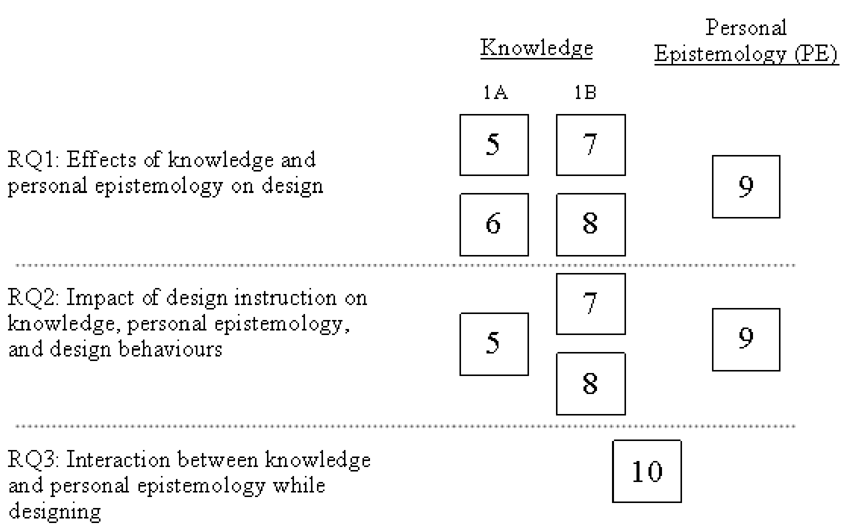


Figure 36 Map of thesis chapters to research questions

A summary of the contents of each chapter are included below for context:

- Chapter 5 described the pre-university experiences for the eight student participants in this study, and analysed those experiences using the factual, conceptual, and procedural knowledge dimensions from Anderson and Krathwohl (2001).

- Chapter 6 described the design process using design timelines (Atman, 2019) for each of the student participants as they designed a device to help a user open a jar single-handed.
- Chapter 7 described the design instruction the student participants received in their first semester design course, and any other experiences each student had prior to the 1B interview. This included working on student design teams, co-operative work terms, and personal side projects.
- Chapter 8 described the design process, again using design timelines, as each student participant solved the problem of designing a device to open a stuck double-hung window.
- Chapter 9 explored the personal epistemology of the students
    - Chapter 9 began by describing pre-university experiences which may have contributed to developing each student's personal epistemology, before presenting an analysis of their 1A design timeline, and evidence from the design activity debrief to attempt to characterize their personal epistemological development using King and Kitchener's reflective judgement model (1994).
    - Chapter 9 then described the epistemic climate of ME 100 and its potential for developing student's personal epistemology, as well as other experiences the students took part in prior to the 1B interview using Rule and Bendixen's integrative model for personal epistemology development (2010).
    - Chapter 9 concluded by presenting analyses of each student's 1B design timeline and evidence from the design activity debrief to characterize their personal epistemological development at the start of their second academic semester.

10.1 Effects of Knowledge and Personal Epistemology on Novice Design Behaviours

The student participants described a wide array of curricular, extra-curricular, and personal activities prior to starting university which could have plausibly developed their knowledge of mechanical engineering design. These experiences included high school courses with instruction and/or projects with design and/or construction elements; team and individual competitions; enrichment programs like Shad Valley; part-time or summer jobs; and personal hobbies and interests. While each student had experiences which could help in solving mechanical engineering design problems, there were **generally three categories of students** based on the quantity and quality of their pre-university experiences:

- Chris with limited relevant experience;
- Jay, Jill, and Patrick with relevant factual/conceptual knowledge but limited procedural knowledge of mechanical design; and
- Michelle, Bond, MJ, and Oscar who had relevant procedural knowledge.

The students were all able to apply useful knowledge from their past experiences during the live design activity in the 1A interviews, but there were some patterns in their design behaviours. There were differences in behaviour between the students – including between students who had similar levels of prior knowledge – however, the **students with relevant procedural knowledge** typically spent more time solving the problem, spent more time generating ideas, and spent more time making decisions and communicating ideas. The **students with relevant procedural knowledge** were also more likely to research the problem space, create detailed drawings, and weigh benefits/trade-offs before making a decision than their less experienced peers. Overall, **students with higher levels of pre-university experience demonstrated more informed design behaviours** than their less experienced peers. Several student participants had noticeable moments in their design process where they did not have the required knowledge to resolve the (sub-) problem they were tackling at the time. These moments occurred at different phases of the design process for different students, for example, Patrick struggled trying to define the manufacturing processes his solution would require to be manufactured, and MJ struggled to identify useful mechanisms to perform a function that his design required. In these situations, the students typically turned to the internet, and in most cases, struggled to find useful information to resolve their difficulty.

In the 1A interviews, most **student participants were exhibiting personal epistemological development in the level four to five**, quasi-reflective thinking stage, with **three of the students demonstrating at least some attainment of reflective thinking** during their interview (Jill, Bond, and MJ). This is higher than has typically been reported in the literature for students entering undergraduate engineering programs; Felder and Brent (2004) in a summary of prior studies found that students tended to enter university at the level of pre-reflective thinking, and graduate at the level of quasi-reflective thinking. The studies cited by Felder and Brent tended to use large-scale quantitative research methods to make these assessments. The instruments used by both Jehng et al. (1993) and Paulsen and Wells (1998) were adapted from Schommer's epistemological questionnaire (1990). This survey asked students questions about knowledge, authority, and learning in the abstract; for example: "Most words have one clear meaning", or "people who challenge authority are over-confident". This is a significant difference from the research undertaken in this thesis, which was situated in context, and presented students with an authentic design task to work – and reflect - on. So, while the sample size in this thesis is insufficient to generalize about novice student epistemological beliefs in the engineering design context, **the findings of this thesis may lend some credence to Hofer's (2020) view that epistemic cognition is situated and contextual**.

There was some **evidence of correlations between level of personal epistemological development and design behaviours** revealed in this thesis. Generating a range of concepts/ideas and revisiting design goals were demonstrated by students of level four or higher, researching the problem space was demonstrated mostly by students of level five or higher, and weighing benefits/trade-offs before making decisions was only demonstrated by a student of level six. The other informed design behaviours did not seem to correlate with personal epistemology to the same degree, and there did not appear to be any patterns when examining design behaviours through the lens of Atman's design timeline patterns. As mentioned in section 9.4.1, **several of the participants in the 1A interviews (viz. Oscar, Jay, and Patrick) showed more**

sophistication in their thinking during the debrief after the activity than they did while designing. Jay, for example, was able to articulate his assumptions and criteria and constraints in hindsight during the debrief in his 1A interview, even though these were never mentioned during the live designing. This may be evidence of these students "stuck" in system 1 ("fast") thinking during the design activity and being unable to slow themselves down and pay attention to their process. Using the language of Schon (1983), these students were perhaps more capable of reflecting-on-action when supported by the interviewer's questions, than they were of reflection-in-action while designing. The differences in thinking demonstrated by the students in 1B between the design activity and the debrief did not seem to be as large as in 1A; perhaps an impact of the design practice they received prior to the second interview.

Prior to the 1B interview, the student participants all completed an introductory course on mechanical engineering and design (ME 100). This course had two parts, taught by two different instructors: Engineering Graphics and Design (EGAD) taught students CAD tools (AutoCAD and SolidWorks), and hand sketching, and gave some opportunities for practicing designing; and Design, Communication, and Professionalism (DCAP) which had a larger focus on design instruction, including several hands-on design activities plus a cornerstone project which ran throughout the term (though was mostly concentrated in the second half of the term). The learning sources for the students were:

- ME 100 focussed on skill development in CAD, drawing, and communication, and importantly for this thesis, included some **factual and conceptual knowledge** instruction as well as a significant amount of **procedural knowledge** instruction.
- The **factual and conceptual knowledge** was taught through anecdotes, small case studies, and hands-on activities and included some knowledge on materials, manufacturing methods, use of tools, and components useful to mechanical engineering design.
- The **procedural knowledge** was introduced in lecture and reinforced through many of the active learning pedagogies used in the course. This knowledge included ideation methods and decision-making methods to a limited degree, and a significant emphasis on one design process which the students were expected to apply in other course activities.

In addition to ME 100:

- Several students participated in engineering design teams (Michelle, Chris, Jill, and Jay) in their 1A term and some worked on relevant hobbies or personal projects (Michelle, Jill, Patrick, Oscar).
- These extra-curricular activities **strengthened existing knowledge** structures in either breadth, or depth, but in some cases, they provided **exposure to new domains** (e.g. Michelle was introduced to manufacturing methods through the student design team experience).
- Lastly, the four 4-Stream students all took part in a 4-month long co-operative work term (Chris, Jay, Oscar, and Patrick), where most were able to learn **relevant knowledge and skills** (Chris may be an exception here, as he didn't feel he learned much of use while working on the assembly line at an automotive manufacturing company).

In the 1B design activity, every student researched the problem space, which was a shift in behaviour from the 1A activity, however, this behaviour mostly stemmed from a lack of knowledge of the appearance and operation of double-hung windows. Other than researching the problem space, the other **most common informed design behaviours demonstrated in 1B were stating design goals and evaluating the solution against design goals** which were also demonstrated by all seven student participants. In this case, it seemed that ME 100 (and to a much lesser extent the 1B design course, ME 101) was successful in teaching all the participating students a method for describing design goals that they were able to put into action even five months after their last instruction in ME 100. The least common informed design behaviours demonstrated by the students were researching the solution space, creating detailed drawings/models, weighing benefits/trade-offs before making decisions, and revisiting design goals which were only demonstrated by four participants each. Of these, **weighing benefits/trade-offs and re-evaluating design goals were only demonstrated by students with relevant procedural knowledge** from their pre-university experiences, plus Patrick (who had more prior experience than Chris, Jay, or Jill). Otherwise, there were very few examples of students applying knowledge from their 1A experiences: their use of sketching was similar to 1A, and no students even attempted to use CAD tools, for example. There was one exception: the **students did use some of the conceptual knowledge** taught to them in EGAD (viz. the scotch yoke mechanism that showed up in two 1B design activities).

The **students in the 1B interviews were demonstrating similar levels of personal epistemology as in 1A**: the majority of student participants were in the level four to five, quasi-reflective thinking stage. Two demonstrated some attainment of reflective thinking (MJ and Michelle), though this is one fewer student at this level than in the 1A interviews where Bond was present at this level. In addition, from the 1A interviews, Jill appears to have regressed to a maximum of level four, while Michelle improved to level six. There were **some correlations between the level of epistemological development and informed design behaviours in the 1B interviews**: the only students to demonstrate the behaviours of weighing benefits/trade-offs before making decisions, and revisiting design goals demonstrated personal epistemologies of at least level five. Students of level five or higher also generally spent a higher percentage of their time in decision-making and idea generation than their peers, though Oscar was an exception here. Lastly, students of level six or higher spent more time in decision-making and in feasibility analysis than their peers.

10.2 Impact of One Academic Semester on Novice Design Behaviour

This section will summarize findings from Chapter 8 where student design activity in the 1B interview was examined, and Chapter 9 which described student personal epistemological development and how it manifested in the two design interviews, with findings from Chapters 5 and 7 which described the experiences and knowledge structures of the student participants prior to the 1B interview to examine the impact of each student's experiences between the time they were interviewed in 1A and the time they were interviewed in 1B. The timing of the interviews for the 4-Stream and 8-Stream students plus the design course instructors are summarized in Figure 37 below.

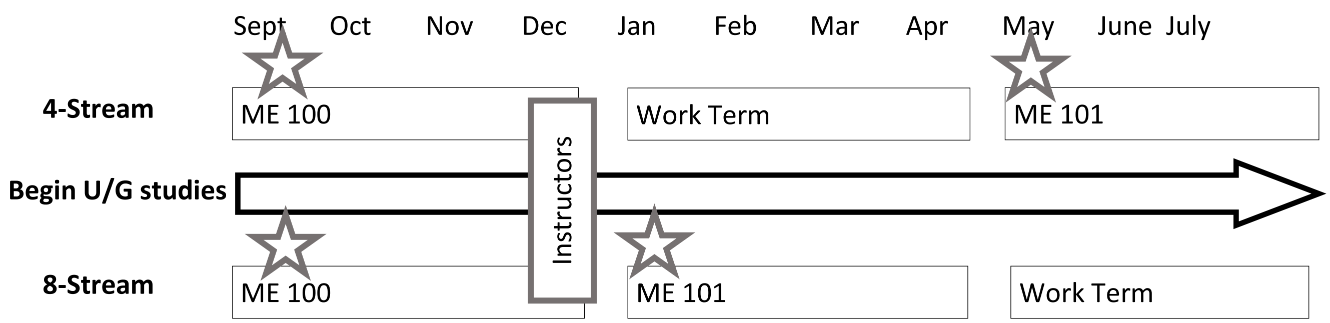


Figure 37 Timing of design courses, co-op work terms, and interviews in first year ME (student interview timing indicated with stars)

Table 52 summarizes the knowledge taught in ME 100 across factual, conceptual, and procedural knowledge types. While knowledge taught does not equate to knowledge learned, this provides a useful summary of potential changes in knowledge domains and levels between the 1A and 1B interviews.

Table 52 Summary of knowledge taught in ME 100

Factual		Conceptual		Procedural	
Domains	Level	Domains	Level	Domains	Level
Materials	Low	Mech. components	Low	Design	Medium
Manufacturing	Low	Construction	Low	Ideation methods	Low
3D printing	Low			Decision-making methods	Low
Design tools	Medium			CAD modelling	High
Construction tools	Low			Rapid prototyping methods	Medium
Crafting	Medium			Machining, manufacturing processes	Low

Table 53 summarizes the changes in knowledge domains and knowledge levels for the seven participants in the 1B interviews for experiences outside of ME 100. The only knowledge domains being presented in this table are ones that are new or existing knowledge domains that have been improved (indicated by an '^' in the table) since the 1A interview. **Overall, there is some evidence of the most experienced students from the 1A interview gaining more new knowledge than their peers**, though Jay also saw significant improvements in both breadth and depth of knowledge. These changes are mostly due to the co-op work terms of Jay, MJ, and Oscar, which the 8-Stream students (marked by 8S in the table) did not have prior to this interview. While Jay increased in knowledge, and so arguably had more experience than Jill going into the 1B interviews, **overall, the groupings of students remain consistent with the pre-university groupings**. That is, Chris remains the least experienced of the seven participants; the second group of Jill, Jay, and Patrick have changed in relation to each other, but are less experienced than the most experienced group of Michelle, MJ, and Oscar.

Table 53 Change in knowledge domains and levels between 1A and 1B interviews

	Factual			Conceptual			Procedural		
	Domains	Relevance	Level	Domains	Relevance	Level	Domains	Relevance	Level
Chris 4S	3D printing	High	Low				Manufacturing 3D printing	High Med	Med Low
Jill 8S	3D printing	Med	Med				3D printing Manufacturing CAD Modelling	Med High High	Med Low High
Jay 4S	3D printing Composites	Med Med	Med ^ Low	Mech. Components	High	Low	CAD modelling 3D printing Design Verification Composites	Med Med High High Med	High ^^ Low Med Med Low
Patrick 8S							3D printing CAD Modelling	Med High	Med High
Michelle 8S							CAD modelling Design	High High	High ^^ Med ^
MJ 4S	Machinery Electronics Program.	Med Low Low	Low Low Low	Machinery Electronics Programming	Med Low Low	Low Low Low	Design CAD Modelling Electronics Entrepreneur.	High High Low Low	High ^ High Low Med
Oscar 4S	Program.	Low	Low	3D printers Programming Mech. Components	High Low High	High Low Med	3D Printing	High	High
^ indicates an increase in an existing knowledge domain									

As summarized in section 8.3.2, looking at student performance through the lens of Atman's design timelines, students spent approximately the same total time on the design activity in 1B, but the standard deviation of time spent was much higher, with 8-Stream students spending more time on the problem on average than 4-Stream students. In addition, the **students spent more time on problem definition in 1B**,

with most participants spending time writing explicit problem criteria and constraints (or requirements), as taught in their first-year design course(s). Figure 38 maps the informed design behaviours demonstrated by each student in both the 1A and 1B design activities. The groupings of students by knowledge level are represented by colour (light grey for least experienced, medium grey for the middle group, and black for the most experienced group), and the academic stream is indicated after the students' pseudonym (4S are 4-Stream students, 8S are 8-Stream).

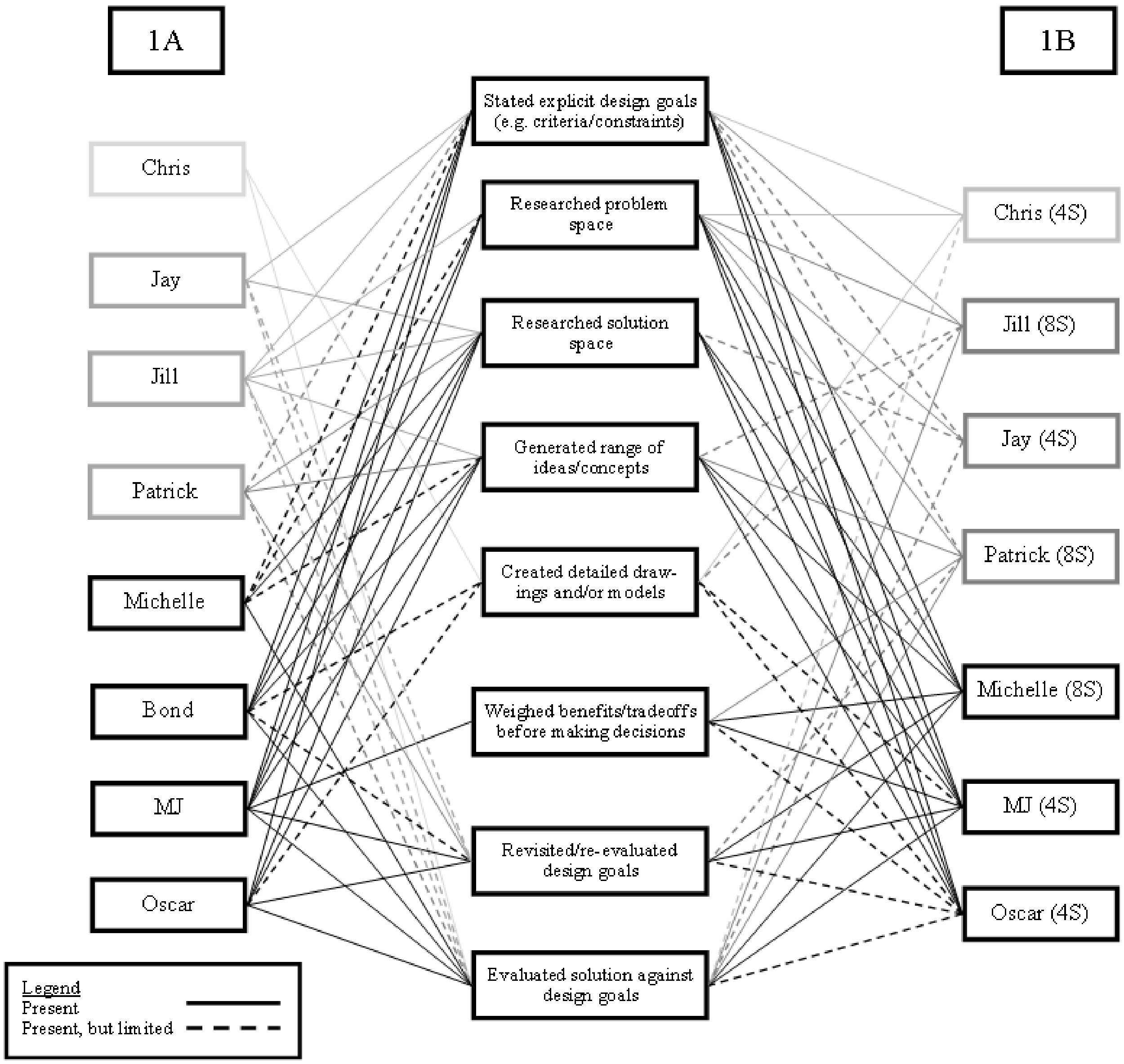


Figure 38 Map of student performance against indicators of informed design behaviours, 1A and 1B interviews

Overall, the number of informed design behaviours seems to correlate more strongly with level of knowledge than with academic stream or work term relevance/quality. In the 1B activity, **more students researched the problem** space (due in large part to lack of knowledge of double-hung windows), **weighed**

benefits/trade-offs before making decisions, and created **detailed drawings** than in 1A; however, fewer students researched the solution space. **Students in the "relevant procedural knowledge" group** – which included Michelle, MJ, and Oscar in 1B – **were more likely to research the problem space, and create detailed drawings than their peers in 1A, while they were more likely to re-evaluate design goals in 1B. In both interviews, these students were more likely to weigh benefits/trade-offs** than the students in the other knowledge groupings. For most students, their performance in 1B was similar to their performance in 1A with the exception of Michelle and Chris who both demonstrated two additional informed design behaviours in 1B over their 1A performance. As discussed previously, Michelle's dramatic improvement is not easy to explain, though the most probable explanations are that she underperformed in 1A based on her level of prior knowledge and experience, or that a lesson or experience in ME 100 was able to build off the base of Michelle's past experiences to improve her performance. For Chris, he demonstrated the fewest informed design behaviours of any participant in 1A, and after his experiences in his first academic term (and his work term), he was able to "catch up" to the performances of his nearest peers (Jay and Jill). In this sense, Chris had more room to grow than many of the others, and his time between the interviews seemed to have been productive for him.

Four out of seven student participants regressed in their personal epistemology in the 1B interview either at the low end of their demonstrated levels (Patrick), the high end of their demonstrated levels (Chris), or across their entire range (Jill and Jay); one stayed the same (MJ); and two improved (Oscar and Michelle). Examining their performance in the design activity through their demonstrated informed design behaviours, five out of seven students improved (Patrick, Michelle, Chris, MJ, and Oscar), one stayed the same (Jay), and one regressed (Jill). Combining these findings, only Oscar and Michelle progressed their personal epistemologies and the number of informed design behaviours they demonstrated. Figure 39 summarizes the performance of all students in both the 1A and 1B interviews, sorted by the level of personal epistemology they demonstrated in each interview. As in previous diagrams, colour indicates the groupings by knowledge with light grey representing the student with the least knowledge, medium grey representing the middle group, and black representing the students with the most knowledge. **In 1A, only students with personal epistemologies of level six (MJ) demonstrated the behaviour of weighing benefits/trade-offs before making decisions, while in 1B, it was only students of level five or higher** (Patrick, Oscar, Michelle, MJ). **In 1B, only students with personal epistemologies of level five or higher revisited design goals**. In the 1A interview, the only students who demonstrated this behaviour were Oscar and students with personal epistemologies of level five or higher. **In both interviews, only students of level four or higher demonstrated the behaviour of generating a range of ideas/concepts**.

Figure 39 shows a mapping of the indicators of informed design behaviours derived from Crismond and Adams (2012) for each student in both the 1A (left side of the figure), and 1B design activities (right side of the figure). The students in the left column are ordered based on their personal epistemological development as assessed in the 1A design interview, while the right column is ordered based on their personal epistemological development as assessed in the 1B design interview. The line colour for each student indicates their relative level of pre-university knowledge, with light grey representing the group with limited relevant knowledge, medium grey representing the middle group; and black representing those with the most relevant knowledge.

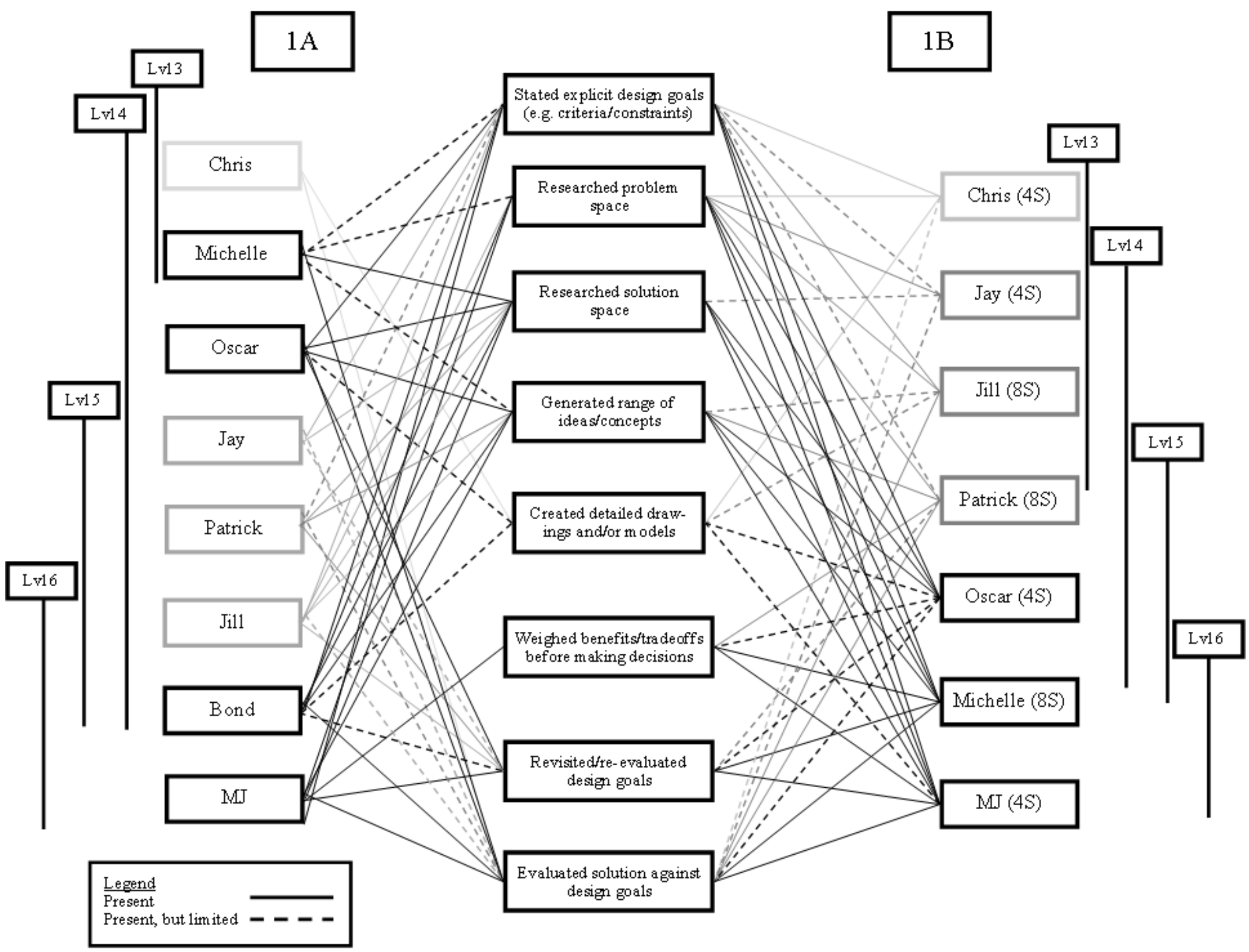


Figure 39 Indicators of informed design behaviour in the 1A and 1B design activities, sorted by personal epistemology at time of interview

Overall, the students' work terms did not seem to lead to any noticeable improvement in the 4-Stream students as compared to the 8-Stream students. Jay's work term seems to have contributed to knowledge development, but that did not lead to any noticeable improvements in his design behaviours in 1B. Similarly, only Michelle and Oscar improved their personal epistemology between the 1A and 1B interviews, and Michelle was an 8-stream student who did not have a work term prior to the 1B interview, and Oscar was a 4-stream student who did have a relevant work term. As for recall of the lessons learned in ME 100, the 4-Stream students did struggle more than the 8-Stream students in recalling the details of the teaching methods used in the course, but they were still able to put the lessons from the course to use in the 1B design activity. This is most evident in the behaviour of stating explicit design goals where **every participant either specified explicit constraints and criteria (as taught in ME 100), or design requirements (as taught in ME 101)**. Interestingly, **their ability to produce detailed drawings or models of their designs in 1B did not improve much**, even with the practical experience of the work term for the 4-Stream students, the experiences in the student design teams either designing or producing real parts for real devices/projects, and the significant time spent teaching detailed design skills in CAD in ME 100.

10.2.1 Other Observations

In the 1B interviews, several other outcomes of their first semester were brought up by different students. This included **evidence of development in the affective domain**. For example, Chris mentioned that he felt much more comfortable in the 1B interview after taking ME 100. Patrick also mentioned that he was more comfortable in the 1B interview than in 1A which had a positive impact on his ability to generate ideas in the design activity. Patrick didn't mention ME 100 specifically, but more that he was re-adjusting to the academic environment after being away from it for a couple years to play competitive hockey. In MJ's 1B interview, he commented on the impact of the toy project being a team-based project. To MJ, the dynamics of trying to keep the other team members happy and contributing made ideation and decision-making more challenging during the project, especially as they had to shape both the "problem" (i.e. the idea for the toy) and the solution in the toy project. Lastly, Patrick and the interviewer had an exchange in the 1B interview about selecting a design process now that Patrick was learning a different approach in ME 101. Patrick struggled to provide an answer to this – he didn't seem to have considered this more meta, procedural question – and so was looking to his future work term employers to help resolve the uncertainty:

> *"depending on how they [the employer] do it might give me a better idea of how the field goes and I'll be biased towards that, obviously, 'cause the work I'll be in… [the ME 101 instructor] again mentioned that… [an employer might say] 'what the heck are you talking about? We only use constraints and criteria', so… I know you said there will be different ways of doing it. I just I think I'll have to get practice with real work… if I'm going to decide"*

10.3 Interactions Between Knowledge and Personal Epistemology

This section seeks to synthesize the analyses presented in Chapter 5 on pre-university experience, Chapter 6 on their 1A design process, Chapter 7 on their experiences prior to 1B, Chapter 8 on their 1B design process, and Chapter 9 on their personal epistemological development to explore the interactions between knowledge and personal epistemology in the engineering design context.

Table 54 summarizes the level of personal epistemology for each student in both 1A and 1B, sorted by knowledge group (level 1 are the least experienced and level 3 are the most experienced students). In the 1A interviews, **there is not a strong correlation between level of pre-university experience and level of personal epistemology**, though the lowest personal epistemology is in the group with the least knowledge, and the highest personal epistemologies are in the group with the most knowledge. This trend changes in 1B as **the students with more knowledge began 1B demonstrating higher personal epistemological development than their peers**. This meant improvements in personal epistemological development after 1A for the more experienced students (viz. Michelle and Oscar), and regressions in students with less experience (viz. Chris, Jay, Jill, and Patrick).

Table 54 Summary of personal epistemological development for each student, 1A and 1B by knowledge level group

Knowledge Level Group	Student	1A	1B
Level 1: Limited relevant knowledge	Chris	3-4	3 *
Level 2: Relevant factual/conceptual; limited procedural knowledge	Jay	4-5	3-4 *
	Jill	4-6	3-4 *
	Patrick	4-5	3-5 *
Level 3: Relevant procedural knowledge	Michelle	3-4	5-6 ^
	Bond	4-6	--
	MJ	6	6
	Oscar	4	4-5 ^
Note: ^ denotes an increase, * denotes a decrease			

Table 55 summarizes Figure 39 to facilitate the comparison between knowledge groups and levels of personal epistemology. For clarity, Bond's data are not included in the table as he didn't participate in 1B. Each row contains the number of students who demonstrated each informed design behaviour, the knowledge group that the least experienced student belonged to (one represents the least experienced knowledge group, two is the middle group, and three is the most experienced knowledge group), and the lowest level of personal epistemology by a student who demonstrated that behaviour. For example, in 1A, there were seven students who demonstrated the behaviour of stating explicit design goals, the least experienced student who demonstrated that behaviour was in knowledge group two, and the student with the lowest level of personal epistemology who demonstrated that behaviour was of level 3-4.

Table 55 Summary of students who demonstrated each informed design behaviour, 1A and 1B interviews

	1A			**1B**		
Behaviour	**# students**	**Min knowledge group**	**Min epistem. level**	**# students**	**Min knowledge level**	**Min epistem. Level**
Explicit design goals	6	2	3-4	7 ^	1 *	3 *
Research problem space	3	2	3-4	7 ^	1 *	3 *
Research solution space	6	2	3-4	4 *	2	3-4
Generate range of concepts	5	2	3-4	5	2	3-4
Create detailed drawings	2	1	3-4	4 ^	1	3 *
Weigh benefits/trade-offs	1	3	6	4 ^	2 *	3-5 *
Revisit design goals	5	2	4	4 *	2	3-5
Evaluate solution against goals	7	1	3-4	7	1	3 *
Note: ^ denotes an increase, * denotes a decrease						

Examining these data, and the other findings in this thesis, there are some trends worth discussing. In the 1B interview, **more students demonstrated stating explicit design goals, researching the problem space, creating detailed drawings, and weighing benefits/trade-offs**, while fewer students demonstrated researching the solution space, and revisiting design goals as compared to 1A. **In 1B, the minimum knowledge level for stating explicit design goals, researching the problem space, and weighing benefits/trade-offs all decreased**. This means that students in a lower knowledge grouping demonstrated those behaviours in 1B as compared to the 1A activity. Similarly, in the 1B interview, **the minimum level of personal epistemology for stating explicit design goals, researching the problem space, creating detailed drawings, weighing benefits/trade-offs, and evaluating the solution against design goals decreased**. This means that students with lower levels of personal epistemology demonstrated these behaviours in 1B as compared to the 1A design activity. As summarized in Table 52 and Table 53, the students all developed knowledge in new domains, and in many cases, were also able to strengthen their existing knowledge domains, whereas only Michelle and Oscar were able to demonstrate thinking that was representative of a higher level of personal epistemology in 1B (with Chris, Patrick, Jill and Jay all decreasing).

Let's examine the behaviours one at a time. Stating design goals was taught and emphasized repeatedly in ME 100 (and again in ME 101 as the students were being interviewed in 1B) and given that all students demonstrated this behaviour in 1B (a slight increase in its prevalence from 1A), **it appears that even students in the pre-reflective thinking level (i.e. level 3 or below) can be taught to state explicit design goals when they design**. Research was included in the "PRIMED" design process taught in ME 100; however, it did not seem to be reinforced strongly in the course assessments. As commented on previously, there was an increase in the number of students who demonstrated the behaviour of researching the problem space in 1B, most likely due to the lack of familiarity with the main subject of the design problem (viz. double-hung windows), as opposed to anything that was taught prior to the 1B interview. This is reinforced when examining the behaviour of researching the solution space, which saw a notable decrease in prevalence in the 1B interviews. Unlike researching of the problem space, which was demonstrated even by a student in the pre-reflective thinking level, **research of the solution space required at least some demonstration of quasi-reflective thinking**. Reinforcing the role of research in all aspects of the design process could potentially be an area of improvement for the course instruction moving forwards, as it is not clear if it is a lack of procedural knowledge or if it requires students to progress beyond pre-reflective thinking. This could also be an issue of skills related to information literacy, which past studies have shown first year students struggle to employ while solving design problems (Wertz, et al., 2013).

The behaviour of **generating a range of concepts was largely unchanged from 1A to 1B** even though "Ideate" was part of the PRIMED design process taught in ME 100, and several other ideation activities took place in the course (both as part of projects, and standalone activities). In both interviews, **this behavior was only demonstrated by students who showed at least some evidence of quasi-reflective thinking**. Given that the instruction on ideation did not seem to be effective in increasing the prevalence of the behaviour, this could be more related to students reaching at least the quasi-reflective stage of personal epistemology before they could be expected to consistently demonstrate the behaviour. **Creating detailed drawings increased in prevalence in the 1B interviews**, and given the extensive effort spent on teaching drawing skills and detailed design in CAD in ME 100, this seems to be another behaviour that can be taught, even to inexperienced students demonstrating pre-reflective thinking. **Weighing benefits/trade-offs before making decisions increased in prevalence in 1B** and was demonstrated by students in a lower knowledge group, and with a lower level of personal epistemology than in 1A. This would seem to indicate that students can be taught to do this as a natural part of their design process, but there seems to be a minimum level of personal epistemology before it is reliably demonstrated. Only students who had at least some attainment of level five, quasi-reflective thinking demonstrated the behaviour in the 1B interview – and only one student who exhibited reflective thinking demonstrated it in 1A.

The **prevalence of revisiting design goals decreased in 1B**. This behaviour manifests when a designer iterates on their understanding or framing of the problem after considering potential solutions. Past research on the differences between designing during a work term versus designing during a university-level course described the student perception of design projects in courses as being "linear" and more constrained in nature than the design tasks the same students experienced in the work environment

(Nickel, et al., 2023). Iterating back to the beginning of the process can seem like taking a step backwards in the design (i.e. a waste of time), and because of the time bound nature of academic design projects, does not occur in courses with much regularity. This may mean that the message that design is iterative – a message that was conveyed with the teaching of the PRIMED design process in ME 100 – is lost on students as it doesn't match their experience of designing in the course. All this is to say, that this is a complex behaviour to teach, and based on the performance of the behaviour in this thesis, may have a minimum level of personal epistemological development before it is demonstrated with any regularity. In this thesis, **only students who exhibited a personal epistemology of five or higher, or who had extensive design experience (viz. Oscar in 1A) revisited their design goals**. Lastly, all students in both interviews conducted at least some evaluation of their proposed solution against their understanding of the problem. This behaviour seems to have few requirements on knowledge or personal epistemology before it is demonstrated, as even Chris in 1A demonstrated the behaviour even though he didn't construct explicit goals during his design process.

Some interesting comparisons can be made between students with similar levels of pre-university experience. From Table 48, in the 1A interviews, **there was a general trend towards more indicators of informed design behaviour in students with more knowledge** (especially with more procedural knowledge), but there is some evidence that when comparing students of similar knowledge levels (e.g. Jill and Patrick, Jill and Jay, MJ/Bond and Oscar, or Chris and Jay), **students with higher demonstrated levels of personal epistemological development also seem to demonstrate more indicators of informed design behaviour**. Looking at one of these comparisons in more detail, Jay and Chris were two of the least experienced students coming into the 1A interview; neither had much relevant knowledge of mechanical engineering design, and yet Jay demonstrated two more indicators of informed designers than Chris in 1A. One difference between these two students is that Jay seemed to have developed his personal epistemology more than Chris and had more design instruction (though it was in the domain of electronics). It is interesting not only that Jay demonstrated more indicators than Chris, but also which indicators they demonstrated. Chris created a more detailed model of his solution than Jay, a behaviour which requires factual and conceptual knowledge of the domain, while Jay communicated explicit design goals and researched the solution space, behaviours that may be more linked to procedural knowledge and/or personal epistemological development as stated above. Oscar and Bond are also interesting to compare as they had similarly high levels of prior experience, and yet that didn't seem to translate into development of Oscar's personal epistemology to the extent as Bond in the 1A interview. Ultimately that didn't translate into much difference in the exhibited indicators of informed designers by each student – Bond only demonstrated research of the problem space that Oscar did not – however, that may have been due to other factors like their respective familiarity with the problem. It is unfortunate that Bond did not continue with the study in 1B as it would have been interesting to see if a gap opened between them after Oscar participated in a co-op work term. This trend is weaker in 1B as summarized in Table 50. Here, Patrick demonstrated a higher upper range of personal epistemology than Jill and demonstrated one more informed design behaviour, but some of the other comparisons don't show any differences (e.g. Chris and Jay). Perhaps this is due to ME 100 narrowing differences between students.

10.3.1 Other Observations

There were various times in both the 1A and 1B interviews where students faced a challenge in the design activity that **they did not have sufficient knowledge to resolve**. In these cases, **the students would occasionally regress in the level of personal epistemology** they were exhibiting as they resolved the challenge. For example, Bond and Jill in 1A exhibited pre-reflective thinking in some of the earlier phases of the design process when they were developing their overall solution concept but reverted to quasi-reflective thinking when working on the detailed design of their solution. It is possible that as students faced higher cognitive loads – or insufficient knowledge – when completing their designs, that they are not able to maintain reflective thinking. A similar thing happened to MJ when he hit the later stages of the design activity; either through fatigue, or through a lack of conceptual knowledge, when he struggled to identify useful mechanisms to solve the sub-problems in his design, he stopped generating multiple design options. Bond and MJ were also able to model more developed personal epistemologies when they were relying on the procedural knowledge taught to them in Shad Valley. In this case, both students were able to slow themselves down early in the design process, generate multiple options for the overall design concept for their jar opening device, and select one based on transparent, explicit criteria. However, as they moved farther into the design activity, this behaviour began to disappear. This can be seen in MJ's 1A design process timeline in Figure 40 below, where sections a through e (which took approximately 25 minutes in total) reflect one round of ideation, feasibility testing, and ultimately convergent thinking to select a concept, as compared to section h and I where MJ goes through all these same processes for the detailed design of his device in much less time (5-10 minutes each).

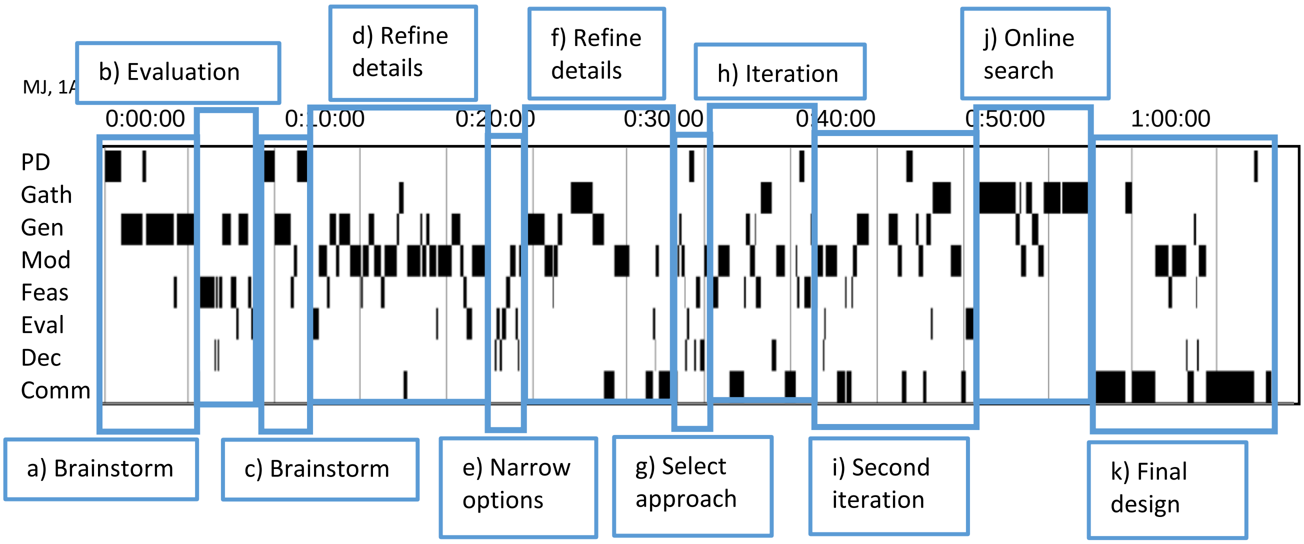


Figure 40 Overview of design process, 1A interview with MJ

From the data presented in this thesis, it is **possible that procedural knowledge can support students in executing informed design behaviours** like generating multiple concepts and weighing benefits/trade-offs before making decisions, even when those students are operating at the pre-reflective levels. MJ's deliberate implementation of the process taught in Shad Valley appears to be one example of procedural knowledge supporting personal epistemology. There are some dangers to this approach – as was reported in Rennick et al. (2018) – where some students reported "faking" the structured decision-making process that was reinforced in their course to obtain the grades on the assessment even though they saw little value in the work of generating multiple options and ranking them on their strengths and weaknesses before selecting one to pursue.

11 Contributions, Limitations, and Future Directions

This chapter begins with the potential contributions of this thesis, including implications for design education, followed by a discussion on the limitations of the study design and analysis methods, and ends with suggestions for future research.

This thesis builds on decades of research into design and problem-solving behaviour of novices and experts. This body of work has largely built a consensus description of the differences between novice and expert designers but investigating student design skills as they transition from high school to university (including investigating the value of pre-university experience), and as they participate in work-integrated learning like co-op has received less attention. Overall, this thesis took a similar approach to Adams et al. (2003) where student verbal protocols are analysed deductively for process and analysed again through the lens of a specific cognitive structure. In the case of Adams et al., they were looking at the role of reflection-in-action while undergraduate students designed solutions to an ill-structured problem, whereas this research examined the role of personal epistemology and domain knowledge.

This thesis contributes to the role of knowledge structures in the learning of engineering design skills, how they differ between students, and how they change over time. These contributions can be leveraged to inform engineering design pedagogies and course structures, helping to establish useful baselines as well as development pathways for students with diverse levels of experience.

11.1 Contributions

There are three categories of potential contributions: contributions to research on how design expertise evolves and develops, contributions to the research methodology on how to study the learning of design expertise, and the contributions to how design can be taught, and the learning facilitated. Each of these areas will be elaborated on next.

There have been few in-depth, longitudinal studies focusing on the design skill development of novice, first-year designers, especially where work-integrated learning is included. Atman et al. (2005) is one of the few longitudinal investigations of student performance. Atman et al. sampled 18 student participants in first year, and again in fourth year, investigating the differences in design performance between freshman and senior students through a verbal protocol study design. Much more common are cross-sectional research designs – see (Atman & Bursic, 1998) or (Atman, et al., 1999), for example – or pre-/post- intervention studies (Atman & Bursic, 1996). As a result, the field is still in its exploratory and preliminary stage. This thesis incrementally contributes to the general understanding of novice, first-year design skills and development in several ways, and these will be detailed in the following subsections.

11.1.1 Contributions to Development of Design Expertise in Novices

There are several potential contributions to the development of design expertise arising from this thesis:

- Recognition of pre-university experiences on student knowledge and personal epistemological development
- Recognition of the connections between specific types of learning with experiences/activities
- Value of longitudinal tracking and analysis of individual student skill development
- Personal epistemological development and knowledge are developed in different ways, and at different times

The 1A interviews revealed that students in this study had a **wealth of pre-university experiences to draw on, though there can be large differences in prior experience from student to student**. The students in this study had relevant high school courses and projects; competition experience from events like FIRST Robotics, hackathons, and skills competitions; STEM enrichment programs like Technovation and Shad Valley; and several had relevant employment experience. The students generally fell into three groups by level of pre-university knowledge, with the most experienced students having benefited from at least some training in the procedural knowledge of engineering design. **Students also showed a range of levels of personal epistemological development, with most demonstrating attainment of quasi-reflective, or reflective thinking in the 1A interview**.

This thesis presented evidence that **while pre-university experiences, level of knowledge, and level of personal epistemological development are related; they are also distinct in some ways**. This is a positive result for the construct validity of the methods used in this thesis, as teaching environments with strong epistemic climates should be conducive to general learning. However, there are many ways to construct a learning environment which can convey knowledge, but which is not at all conducive to developing one's personal epistemology. Generally, students with more and/or higher quality pre-university experiences had more knowledge, and more developed personal epistemologies, but the correlations could be quite weak, and these differences did not always result in more informed design behaviours when solving a design problem. However, there was some evidence that once a student had received training in engineering design, these correlations strengthened.

The longitudinal nature of this study presented an interesting opportunity to investigate how design skills, factual, conceptual, and procedural knowledge, and personal epistemological beliefs "decay" (or not) over time. Ebbinghaus (1913) proposed the "Curve of Forgetting" which states that unless a person spends effort to move information from short-term to long-term memory, they will have forgotten ~90% of what they learned within 30 days, and it is feasible that design knowledge and skills could face a similar decay if not reinforced. In general, there was not much evidence of decay in either the 8-Stream students (who had gone about 30 days since the last instruction in ME 100 to the 1B interview) or the 4-Stream students (who had four to five months between the last ME 100 instruction and the 1B interview). Significant lessons from ME 100 were not simply recalled by the students but were put into practice in the design activity; most notably, the approach of using constraints and criteria to develop goals for the design activity. The opening section of the 1B interview, which probed their experiences prior to the interview, no doubt assisted with recalling their prior experiences, which is one of the limitations of this study design. There also were topics that were taught by the ME 100 course instructors that were not as universally recalled by the student participants, but it is not clear if that is a result of forgetting, or of not having internalized those lessons when they were taught. Overall, **most students did not seem to develop their personal epistemologies in the time between the 1A and 1B interviews, but they were able to develop their knowledge. In the 1B design activity, the students were able to put the factual, conceptual, and procedural knowledge they learned into action, and while they spent approximately the same amount of time solving the design problem in the 1B interview as in 1A, they demonstrated more informed design behaviours**.

11.1.2 Methodological Contributions to the Study of Design Expertise

Several potential contributions to the methodology associated with the study of design expertise arise from this thesis:

- Methods and techniques for studying personal epistemological development in situ
- Types and level of questions used to access the student skill and knowledge

Over the last 25 years, there has been a growing recognition of the usefulness of intellectual development models like those proposed by Perry (1970) and King and Kitchener (1994) in engineering education (Felder & Brent, 2004) (Chance, et al., 2019). King and Kitchener emphasize the importance of their model of intellectual development when people are solving ill-structured problems, of which design problems are some of the most ill-structured (Jonassen, 2000); however, there has been little investigation into how personal epistemology interacts with designing and design education. Rennick, et al. (2019) reported on an investigation into the personal epistemology in the context of introductory software design projects through a retrospective interview at the end of a course project using Perry’s model of epistemological development (1970). Zhu et al (2019) interviewed students to explore demonstrations of relativistic thinking in project-based learning environments, also using Perry’s model. Bernhard et al. (2019) studied architecture and design students in situ in a design studio setting, examining how students use “epistemic tools” as means of creating shared understanding in a team setting. This thesis builds on the findings of Zhu et al. (2019), who recognized some of the ways relativistic thinking presents itself in project-based learning environments, and the approach in Rennick et al. (2019) (which was conducted with design teams). **The key methodological contribution of this thesis is the approach used to investigate personal epistemological development while students solve a design problem in situ.** This approach facilitated the investigation of relationships between knowledge, personal epistemology, and design behaviours; highlighting the ways knowledge and personal epistemology develop together and separately, and their different roles in the design behaviours of novices.

The **levels of personal epistemological development reported in this thesis were higher than has generally been reported in past studies** on personal epistemological development in engineering students (Pavelich & Moore, 1996). One past study even found that very few students were able to reach relativistic thinking by the time they graduated from their undergraduate degree (Wise, et al., 2001), which is quite different from these results where two students were showing evidence of relativistic thinking in the 1B interview. Other past research investigating personal epistemology – including engineering education research – has relied on interviews with students to elicit evidence which reflects their beliefs. These interviews are often quite long, require specialized training to conduct and analyse, are not domain specific, and while they produce high quality data, they are inefficient in the sense that an hour-long interview is required to capture evidence of a single cognitive dimension (Pavelich & Moore, 1996) (King & Kitchener, 1994) (Marra, et al., 2000). King and Kitchener recognized the limitations of their interview method, which asked participants to comment “on the spot” to a series of intellectual challenges (King & Kitchener, 1994, p. 104). This thesis **approached data collection using a different approach: instead of using general questions about how the participant views knowledge; these views were collected using the live design exercise and retrospective interview**. With more validation of this method, this approach could lead to more accurate representations of participants’ personal epistemology as it relates to designing “real” devices in-situ. It is highly possible that the differences in reported levels of personal epistemology manifested from the differences in data collection and analyses methods as epistemology has been theorized to be context-dependent (Hofer & Bendixen, 2012), and this thesis was conducted in the mechanical engineering design context and not a generalized domain. As has been argued in papers on the philosophy of engineering and science, where science is focussed on finding absolute “truth”, engineering design is contextual and pluralistic due to the wide variety of value judgements that can be made in producing an engineering solution, and subject to uncertainty (Goldman, 2004), and perhaps students inherently recognize these qualities when they practice design. Future research investigating personal epistemological development would benefit from carefully considering the context of interest when selecting a method.

Overall, this integrated research method may be a **more efficient, and more accurate**, means of assessing personal epistemological development in the engineering design context than past approaches.

11.1.3 Implications for Design Education

There are several potential contributions to the education of design:

- Understanding of pre-existing knowledge and skill schemas of novice designers, and the role these play in design behaviours prior to formal instruction
- Clarification about what might be assumed about student skill and ability
- Possible suggestions for improved promotion of personal epistemological development in first year courses
- Replication of the presence and influence of the affective domain of novice designers
- Identification of the types of support(s) which could benefit students during their learning of design
- Insights into the heterogeneous nature of the students' skills and knowledge when it comes to a cognitive skill such as design
- Understanding the minimal impact of a single instance of work integrated learning at the novice level (i.e. a co-op term) and how this might be related to the type of work done by junior students

With better understanding of the roles of factual, conceptual, and procedural knowledge, and personal epistemology, in "good designerly behaviour", new pedagogies could be developed which are more effective, or more efficient at improving student design skills. Undergraduate curricula are largely a zero-sum game, so increasing the effectiveness or efficiency of design instruction is very desirable. If we understand what differentiates students who produce "good" designs versus "weak" designs, we may be able to design better interventions which can more rapidly develop student design skills or could enact more effective design curricula which span an undergraduate degree. This section will discuss the implications of this thesis on the first design course in the curriculum, followed by the implications of the findings on work-integrated learning pedagogies, and end with a discussion of the implications on subsequent design courses in the curriculum.

11.1.3.1 Implications for a First Course in Engineering Design

This thesis contributes to the understanding of what pre-university experiences novice designers bring with them to the undergraduate classroom, and what role those experiences can have in their design behaviours prior to formal design instruction. The role of pre-university experiences in design instruction has been highlighted by "asset-based approaches" to instruction (Budinoff & Subbian, 2021). Asset-based approaches seek to highlight the strengths (or assets) that students bring with them including language skills, community networks, lived experiences, and the types of technical experiences highlighted in this thesis. These approaches seek to build students' identities, sense of belonging, and self-efficacy through activities like asset mapping, and are beginning to appear in engineering design education (Budinoff, et al., 2022). These approaches use structured methods to guide participants through the process of recognizing their assets, leading to a graphical map. Budinoff et al. (2022) found that students tended to focus on the technical skills in their maps and struggled to identify other assets. The process of collecting prior experiences from the students in this study revealed that students also struggle to identify past experiences with technical relevance, and even once they recall a past experience, they struggle to understand how the experience relates to a personal strength. The questions employed in this study were created to guide students through their past experiences and collect relevant details on the experience in order to understand the impact of that experience on the student's development. **This approach could be useful to supplement asset mapping exercises to draw out more complete maps of technical strengths.**

This thesis highlighted that there is often much that is assumed about the knowledge of novices – both knowledge that they are assumed to have, and knowledge that they are assumed not to have. The most obvious example of a false assumption of knowledge was the choice of a double-hung window for the 1B design problem; a concept that all seven students were unfamiliar with. Unfortunately, the false assumption that students would understand what the question was asking drove student behaviour in a particular direction: they all had to go to the internet to look up the operation of the window. For the purposes of this study, the choice of problem may have masked differences in behaviour of the various participants as it all but ensured that research of the problem domain was a part of all seven participants' processes. When thinking of design education, it does highlight one important consideration: care is required when selecting design problems for the classroom environment. If this thesis is any indication, the nature or subject of the problem can drive student behaviour in specific directions, and so this can be employed as a tactic to focus student attention on specific parts of the process. For example, intentionally picking a problem which few have experience with will require research be a part of their process. While it is outside the scope of this thesis, this relates to Jonassen's design theory of problem solving (2000), which states that a problem is characterized by its variation, and its representation. The problem context is part of the problem's variation (along with complexity and structuredness), but an instructor is also in control over the problem's representation, which includes the level of information provided and the level of fidelity. In the case of this thesis, very little information was provided, instead students were encouraged to search online for missing information. These two independent aspects of a design problem are both in the instructional designer's control, and it is important to understand students' prior knowledge, so the appropriate difficulty is selected, and students spend their time and attention on the issues that are important to the instructor (see Rennick et al., 2022 for further discussion).

This thesis revealed that improvements could be made to the epistemic climate in first-year design courses to better promote personal epistemological development. From the data summarized in section 9.2, there are opportunities for design instructors to better demonstrate their epistemic cognition and additional and/or improved epistemic resolution strategies. Frequently, the only resolution strategies employed are summative design reports after a project has completed. Design documents could be thought of as an argument for solving a particular problem in a particular way, and in the curricular setting, the structure of the argument is reinforced in how design reports are constructed. The obvious limitations of written design reports are that the design is represented as a linear story from a problem statement, through design goals, concepts, decisions, and construction (and occasionally validation) of a prototype. The perception that classroom design processes are more linear than in real design environments was one of the structural differences students saw between their work term environment and the classroom (the other differences were dealing with real clients/users, project transitions at start and end of term, resource coordination, and collaboration) (Nickel, et al., 2023). If design reports don't require details on iteration(s) or designs which were rejected, and justification for the choices that were selected, it not only weakens the argument for the chosen design, but it could also lessen the importance of these steps in students' minds, negatively impacting the opportunities for epistemic doubt and resolution strategies.

While outside the scope of this thesis, it is worth briefly discussing the affective domain of designers. Nickel et al. (2024) found that students in a design environment during their work term must confront sometimes powerful emotions when dealing with uncertainty, authority, and adversity in the work term setting. They also had to control stressors related to fixation, clarity of design goals, availability of information, and environmental factors; they need to understand their role within a team of designers and empathize with their peers; and have confidence in their design skills and knowledge. **There was some evidence in this thesis of students who struggled with the affective demands of the interview**. For example, a lack of motivation in the 1A interview resulted in a change of the instructions for all future interviews. Other students expressed a lack of motivation and creativity as they were designing. Student confidence and motivation are crucial if they are to progress to higher levels of proficiency. Hoffman et al. (2014) describe the requirements for achieving high efficiency as: constant "stretching" of the skill by solving increasing challenges, high levels of intrinsic motivation to work on difficult problems, practice with rich, meaningful feedback, and practice based on mentoring or expert guidance. More attention could be paid to the affective development of students in early design courses in the curriculum, in particular creating opportunities to foster intrinsic motivation.

The results of this thesis highlight that novice designers need support as they develop the factual and conceptual knowledge of the domain. In several interviews, the students went to the internet to find answers to questions they had about their design, and in most cases, they were not very successful in finding answers. In some cases, this was because of a lack of vocabulary, such as recalling the word “iris” in relation to a mechanism that could clamp a circular object, and in other cases, the students didn’t know what to search for. One of the most powerful tools to supplement the lack of knowledge, and to assist with these information searches might be large language models (LLMs) like ChatGPT. With these tools, students can be imprecise in language and can ask follow-up questions to either learn more information, or to clarify what the generated text meant. This approach was tested in fall 2024 by the author with first-year mechanical and mechatronics engineering students to modest success. The students were led through a workshop where they practiced using LLMs in support of designing a solution to the very problems presented in this thesis. The students practiced using LLMs to research the problem, to generate concepts, to research partial solutions once they had decomposed the functions of their overall concept, and to help with detailed design. More work is needed to understand how students use these tools when designing in both the classroom, and industrial settings; and especially on whether there are any long-term repercussions to their use on development of design expertise, but they represent a promising tool to support novice designers as they develop their knowledge of the domain.

The results of this thesis highlight the unique experiences, desires, and motivations in first-year mechanical engineering students; a group that is often thought of as a homogeneous group. These results could impact the future evolution of introductory design courses in the pedagogies employed, and in the assessments used. Early assessments of student experiences and design behaviours using methods like those employed in this thesis could help the instructor understand the starting point for their class and could help students recognize their own strengths and weaknesses. There are several benefits of better understanding the starting point of their students. With a better understanding of the knowledge needs of the class, an instructor could emphasize material to respond to a perceived weakness (for example, conceptual knowledge of common mechanisms, or factual knowledge of fundamental components could be emphasized in design examples provided by the instructor). An instructor could also use these early assessments to monitor wider changes in the experience of the student body, informing continuous improvement and evolution over multiple offerings. For students, if they better understand their own strengths and weaknesses, they could be more deliberate with the extra-curricular activities they pursue or could better communicate their value to prospective co-op employers. Getting students in the habit of identifying weaknesses, seeking out opportunities to improve, and monitoring changes over time is a crucial component of life-long learning in the engineering discipline.

11.1.3.2 Implications for Work-Integrated Learning as Design Pedagogy

This thesis contributes to the understanding of the value of work-integrated learning (WIL) experiences like co-op work terms on the development of novice designers. Table 40 in section 7.4 summarized the knowledge domains that each student could have plausibly developed based on their experiences outside of ME 100. From this table, the **4-Stream students were able to develop more breadth of experience than their 8-Stream counterparts, and this breadth appears to be more evenly distributed across factual, conceptual, and procedural knowledge than from their experiences in ME 100** (which were heavier on factual and procedural knowledge than conceptual). It is also clear that these experiences are very much non-uniform; one student seemed to draw very little value from his co-op experience, and as the least experienced student coming into university, the work term may have widened the gap between him and his 4-Stream peers instead of narrowing it.

Most of the students in this study regressed in the level of personal epistemological development they demonstrated in the 1B interview. Of the two students who progressed, one was a 4-Stream, and one was an 8-Stream student. **The co-op work term then, had little to no impact on the personal epistemological development of the 4-Stream students**. While it was challenging to evaluate the epistemic environment within these co-op work term settings, or within the student design team environments in which the students were working; it is possible that these environments did not have an epistemic climate that was conducive to personal growth. There could be numerous reasons for this; one observation from this thesis is that the employer-employee power dynamic, and even the difference in age between supervisor and co-op student (and thus perceived difference in engineering experience), may negatively impact the epistemological development of students in these settings as the social dynamics reinforce pre-reflective thinking. In addition, as the focus in an industrial setting is not to train the co-op students, but is instead to complete tasks that further the interests of the company, of the four components that make up the epistemic climate of the environment according to Feucht (2010), it is unlikely that a co-op student supervisor is modelling their personal epistemology, or providing epistemic instructions that could contribute to student development, especially in a first work term. Another way to look at this is through Rule and Bendixen's Integrative Model (2010) described in section 2.2.1. While the real-world industrial environment is no doubt riddled with opportunities for a student to feel epistemic doubt; the promotion of resolution strategies, metacognition, and even reciprocal causation are much less likely than in a classroom environment where these elements can be structured into the course teaching and learning activities.

The **work term experiences of the 4-Stream students did not seem to have much of an impact on the 1B design activity**. Students in 4-Stream did not demonstrate much, if any, knowledge that was acquired during their work term, did not develop their personal epistemologies more than their 8-Stream peers, and improvements in their demonstration of informed design behaviours was approximately the same as with the 8-Stream students. There could be numerous causes for this, for example, this could be the result of a mismatch in problem domains between the work term and the design activity, or the result of the design activity concluding before a prototype was constructed (and so their "know-how" in assembling a physical device was not put to use). Or, as noted above, if the epistemic climate of the work term environment is not conducive to development of personal epistemologies, perhaps there need to be interventions once the students return to their studies on the university campus. These interventions could be part of subsequent design courses, where the instructor assists students in reflecting on their work term experiences, helping students internalize the knowledge they gained, or perhaps providing resolution strategies to promote epistemic growth. It is evident from the student descriptions of their work term experiences that most co-op experiences were valuable, but students may need support integrating this newly acquired breadth of knowledge and experience with their prior knowledge, and with the content taught in the curriculum before they are able to leverage it in the design setting.

11.1.3.3 Implications for Subsequent Design Courses in the Undergraduate Curriculum

The design activities and analysis methods in this thesis could be used as training and diagnosis tools in the educational setting. Design timelines have been used to help teach the design process and highlight the behaviours of expert designers for many years (Atman, 2019). Other approaches have had (typically teams of) students solve design problems and simultaneously track their process in a design timeline; an approach which is rapidly growing in use in educational settings (Atman, 2024). The activity debrief questions could also be used as reflective prompts in the classroom setting, either as part of reflective reports on a design problem, or in mentorship settings where an instructor wants to probe the decision-making process and thinking of their students. Instructors can also be more deliberate with demonstrating their own personal epistemologies, modelling the type of thinking that is required to reach higher levels of proficiency in design. This could be done through a think-aloud designing session where the instructor is solving the problem and describing what they are thinking; an approach described decades ago by the term "cognitive apprenticeship" (Brown, et al., 1989). The problems used in this thesis, and other similar problems summarized by Litster and Hurst (2021), can make for excellent classroom examples, and even for a novice designer, can be solved within a single class period. For domains outside of mechanical engineering, there is a comparative dearth of representative domain-specific problems like the ones in this thesis, and so they may need to be generated by the instructor.

From this thesis, there may be **interactions between procedural knowledge and personal epistemology, where a strength in one, can help cover for a weakness in another**. Procedural knowledge gained in pre-university design programs, for example, seemed to support informed design behaviours and reflective thinking early in the design process. As students moved into other parts of the design where they had less experience, behaviours regressed somewhat. For design instructors, this is a positive sign, that teaching good procedural tools like setting design goals using criteria and constraints, can help students practice informed design behaviours, and simultaneously practice thinking at higher levels of personal epistemology. It is precisely these types of epistemic instructions that King and Kitchener (1994) theorized would help develop personal epistemologies.

In the context of this study, it appears that **the instruction on setting design goals using criteria and constraints in ME 100 was quite successful**, but there is opportunity to support students in performing other informed design behaviours including gathering information throughout the design process (e.g. through research on the problem or solution, or prototyping), or the appropriate use of design tools to create detailed models (e.g. through the use of CAD software). It is perhaps unrealistic to expect that a single course can instill all desirable behaviours in students, and so subsequent design courses will need to carefully assess students' knowledge, development, and behaviour early in the course to maximize (or even individualize) the learning in the course. Subsequent courses are clearly important to continue student learning of design through mechanisms like deliberate practice, but every semester that goes by increases the variance in student experience and so later design courses may benefit from including elements of individualization for students. Asset-based approaches described earlier in section 11.3.1 could be especially useful in later design courses to help students take stock of everything they have learned across courses, co-op work terms, and extra-curricular experiences. Results from these activities could inform learning interventions by the instructor and life-long learning in the students.

11.2 Limitations

As with any research, there are limitations and trade-offs present in this study design. Methodological limitations of the study design will be discussed first, followed by limitations of the findings, and lastly limitations of the analysis methods used.

11.2.1 Methodological Limitations

The first limitation of this thesis is that the **protocol used deviates from those used by Atman and her colleagues in both length, and in the nature of the assigned problems, making comparisons to their results potentially spurious**. The interview protocol was designed to be as brief as possible, while still providing enough data to meaningfully understand each participant. To achieve this, the design exercise is shorter than the playground design problem Atman et al. used for many of their studies (90 minutes versus three hours for Atman) but is longer than the "ping pong" and "street crossing" design problems Atman used in other studies (which were 30-minute designs). This thesis also selected problems which align with the level of students being studied and better represent a problem which required knowledge of the mechanical engineering domain. It is possible that the different design tasks used in this thesis – though they are both derivatives of existing problems used in the literature – make comparisons to Atman's research invalid. Indeed, the differences in the problem statements in this thesis were seen to change student behaviours in measurable ways: all students went online to research what a double hung window was in the 1B interview as they were not familiar with the term, which perhaps led to more time gathering information than a problem which was more familiar to the participants. The impacts of these differences in research protocol on the results should be minor, as comparisons to Atman's results are not leveraged to explain the differences between the students under study, and the behaviours of the novice designers in this study are similar to what was reported by Atman (2019) and by Crismond and Adams (2012).

One other limitation of this study design derives from **the lab-based environment for the design exercise**. This was not a typical setting for students to be designing in, though they had free access to any external resources they would normally have during a design activity (e.g., sketching materials, internet searches, reference material, etc.) In situ observation while a student designed a product during a co-op work term (for example) would be a more realistic setting, but that would present other logistical challenges. The interview protocol described in this proposal had an expected length of two-three hours per participant, per interview. The length of the interview could have created **issues of fatigue with participants**, where the quality of their responses may have decreased over the length of the interview. This was perceived to a certain degree in the design activities that lasted for more than 45 minutes. In addition, participants received some remuneration in recognition of their time and effort in this study, but there were limited external motivators to compel participants to take the design activity seriously. It is conceivable that the **participants did not commit their complete effort and attention to the design task**, which could lead to a weaker overall design than that student would otherwise be capable of. Indeed, this was present in the very first interview, leading to the adjustment of the interview protocol for all subsequent interviews. There is little that can be done if a participant is unwilling to commit significant effort to the design task, but the design task was chosen to be one that participants would hopefully be intrinsically interested in solving. The students also self-selected to be participants in the study, and so they likely had an existing interest in design. The lab-based setting of this thesis research should have minimal impact on the validity of the research results. Lab-based verbal protocols are a very common approach to understanding not just design cognition, but expertise in general, and was the method used in all of Atman's studies.

The third methodological limitation is that **the interviews themselves were a form of treatment with the participants**. Each section of the interview presented slightly different opportunities to impact student behaviour either during the interview, or afterwards. **The background section of the interview could conceivably activate relevant prior knowledge** that students then found useful during the design activity. This could be either a positive impact – for example by reminding students of their breadth of experience – or a negative impact – if students get stuck thinking of a single domain of experience during the design activity. The **design activity itself also provided students a chance to practice designing** that non-participant students did not receive, and while no feedback was given to students on their performance, the design activity was a chance to practice applying their design skills to a realistic task, and the debrief questions were a form of reflection on what the students did to solve a design problem. Lastly, **the post-activity debriefs led participants through a reflective exercise on their designing**. It is well understood that reflection is a crucial component of designing (Schon, 1983), and is a known mechanism for improving student learning (Ambrose, et al., 2010), and so could lead to improvements in their design skills that non-participants did not benefit from. From a study design perspective, the post-activity debrief is an important part of protocol analysis as described by Ericsson and Simon (1996); however, the pre-activity investigation of student experience is a deviation from both Ericsson and Simon, and from Atman. Impacts of any learning from the first interview on the second were minimized by the duration of time between the interviews (four to eight months), and through the selection of a new problem in the 1B interview which did not have any features in common with the first design prompt. The impact of the interviews as a treatment may limit the generalizability of the findings to the rest of the students' peers in their respective cohorts but should have minimal effects on the subsequent performance of the students in this study.

11.2.2 Limitations of the Findings

A significant limitation of this thesis was the small number of participants interviewed. This research sought to interview 10 total students (split evenly between the 4-Stream and 8-Stream cohorts) and ultimately interviewed eight in 1A and seven in 1B. The interview and analysis methods were involved and time-consuming, and while this allows for a deep investigation of each participant, this limited the total number of participants who volunteered for the study, and so generalizable findings for the entire cohort are not possible. This is not the goal of case study research but is nonetheless often a desired goal of educational research. Research using verbal protocols to understand design thinking tends to have small numbers of participants; for example, Atman and Bursic (1996) included a total of 10 students. While Atman's later research included larger numbers of participants as they sought statistical significance in the patterns of behaviour analysed using design timelines, collecting these data took many years.

Self-selection of the participant pool also may have introduced issues with representativeness of the sample. In general, participants who agreed to be interviewed were likely interested in design and so may not represent the average student in their cohort. As the only purposive sampling being done for the participant pool was by stream, it is also possible that underrepresented communities of students were not well represented in this study (e.g. LGBTQ+ identifying students, black or indigenous students, etc.). The only demographic information that was collected from the participants was their gender identity; of which 25% of the participant pool identified as female, which closely matches the makeup of the student body in Mechanical Engineering, though both female-identifying students were from 8-stream. The small sample of students in this thesis, combined with the bias introduced in the sample of students self-selecting to participate, makes it challenging to evaluate the representativeness of the sample to the entire student cohort. Sub-populations in the sample (e.g. students with limited relevant experience, female students, international students, racialized students) by extension, are also very small, limiting the conclusions that can be formed on the data collected. The case studies in this thesis also only represented a single program at a single institution, and so the findings may differ in subsequent work, especially as the context changes. This limitation in the study population was countered by the depth of data presented and analysed in this thesis, and the use of student quotes to convey their thoughts to the reader. The "rich, thick" (Creswell & Creswell, 2018) descriptions of the data in this thesis allows the reader to draw their own conclusions on how representative these students were to other cohorts they might be familiar with.

Relying on novices to report on their past experience, to accurately describe their thinking while designing, and to subsequently report on their thinking are also sources of potential issues. When recalling their past experiences, the participants may not have provided a complete and accurate report of their background. Although care was taken when crafting the questions about their experience, relying on self-reporting of this information risks recall errors and/or omissions, and will miss experiences that may not have seemed relevant, but which may have nonetheless informed their development. In a recent paper, Shealy et al. (2023) found students who were asked to think aloud while designing spent less time designing, included fewer words in their sketches (though ultimately may have communicated more when considering the information carried in their speech), and required more neurocognitive resources than similar students who were not required to think aloud while designing. There was evidence in this thesis that the student participants did struggle with thinking aloud while designing, impacting the quality of the data collected on a small number of the students. These issues, which may be more acute with novices than with more experienced designers, would potentially present an issue when comparing these results with studies of expert designers. In the context of this study, these issues should have only minor impacts on the findings as the time between interviews was small, and the behaviour of the students across time was consistent (e.g. if a student struggled to vocalize thoughts in 1A, they also struggled in 1B).

During the design activity, novice participants may have struggled with the cognitive complexity of the task, and/or may not have the language to describe their thinking which could limit the completeness and/or accuracy of the verbal report. Throughout many of the interviews, the participants struggled with vocalizing their thoughts as they designed their products. During the post-design retrospective interview, novices may struggle to recognize or describe thinking that was largely System 1, or automatic thinking. For example, decision-making shows up very little in many of the design timelines, and yet a solution to the design activity was presented (implying decisions were made). It is possible that the students were making decisions during the activity, but as they struggled to think aloud while designing, this activity may have been lost to the interviewer. If a participant doesn't recognize instances of decision-making, they will struggle to comment on how/why they made those decisions. There were also several instances where the students were able to give more detail on their design process in the debrief than they were capable of during the design activity itself. Ideally, this thesis would have included additional design activities to move students past the initial learning curve of this style of design activity. Additional training may have helped with some of the students who struggled to vocalize their thoughts while designing, though this thesis did employ the use of warm-up activities to give the students practice at thinking out loud. The use of warm-up activities is recommended by Ericsson and Simon (1996) and is common in other design research that uses think-aloud protocols (Tang, et al., 2011).

It is conceivable that the design tool choice (pen and paper) prevented students from completing detailed designs, which was one of the indicators of informed design behaviour that was exhibited by very few participants. Most of the participants did not end their design activities in either term with detailed designs; most completed only conceptual sketches of their solution. Related to this, none of the students tried to use CAD software during their design activity (or even asked whether they were allowed to or not). Prior to the instructions of the design activity being read to the participants, the interviewer gave the students an opportunity to grab paper and writing tools. It is possible that students interpreted this instruction as an expectation that their designing can only be done on paper, and not on their computer (though some did use electronic tablets for their sketching and notes instead of pencil and paper). Completing detailed designs using pen and paper is challenging, and in EGAD, hand sketching is typically described as a communication tool to get ideas across, and not as the final documentation for communicating completed designs. Pen and paper is commonly the medium used to communicate design intent during design cognition experiments, and one past study which compared design processes for subjects who used digital versus traditional sketching environments found no statistically significant difference in process between the two environments (Tang, et al., 2011). Since the experimental method was held consistent from the 1A to 1B interviews, the impact on the findings should be minimal.

Lastly, these interviews took place between September 2021 and May 2022 during the Covid-19 pandemic. As such, **teaching and learning methods both prior to, and during, the time under study were widely disrupted**. The primary means of disruption was a shift from in-person instruction to an emergency remote teaching environment which is defined as a temporary shift to online delivery due to crisis circumstances (Hodges, et al., 2020). The research presented in this thesis was careful to describe the types of learning environments these students experienced to help convey the reality of their training; however, future research under more normal instructional conditions may uncover different findings.

11.2.3 Limitations of Analysis Methods

One source of potential errors in the analysis of the design activities lies in the sole interviewer/coder for this work. The same person conducted all the interviews alone and completed all steps of the analysis alone. While care was taken to maintain consistency in the coding of the interviews, especially as it pertains to the design timelines, where the codes from Atman and Bursic (1998) were used; the primary coder for this thesis research was not formally trained in these methods, and without an additional coder, it is not possible to evaluate the consistency in the coding. The chances of rater subjectivity introducing errors in the coding can not be dismissed, especially when considering the difficulties some students had with vocalizing their thoughts (and thus with the reduced quality of some of the recordings). Having said that, the analyses of the design activities occurred over several years: the initial design timelines were constructed beginning in early 2022 and were completed by mid-2023, while the detailed analyses of the design activities began in late 2023 and completed in mid-2024. This provided opportunities for the primary researcher to verify the consistency of earlier analyses a year, or even two, after they were initially completed, ensuring that all memories of the earlier analyses had been lost by the coder. These verifications occasionally led to small revisions in the categorization of design activities, however, these revisions were rare.

The **data collection and analysis methods for evaluating student personal epistemological development through observation of an engineering design activity is a novel approach and so is largely untested**. Prior research conducted in Rennick et al. (2019) used a similar approach, but the interviews were with design teams and focussed on a longer duration team-based design project. That research also relied on Perry's (1970) model, and was less granular, as it was mostly concerned with whether students had progressed to relativistic thinking in the software design context, or not. In general, having students debrief and discuss an authentic design task as a way to evaluate their personal epistemology is a radical departure from the approaches taken by Perry (1970), or by King and Kitchener (1994); however, it better aligns with more recent thinking of personal epistemology which has found it is not a general trait, but is tied to specific problem contexts (Hofer, 2020). Further use, and especially validation, of this method in the engineering design context is warranted to evaluate the effectiveness of the approach at discerning the level of personal epistemological development as a separate construct from knowledge (in particular, procedural knowledge which may be masking, or boosting, the perceived level of development).

11.3 Suggestions for Future Research

This thesis focussed on mechanical engineering students and design problems, as that is where the bulk of the engineering design literature has focussed to date. There are many opportunities to extend this line of enquiry to other engineering disciplines, which could lead to different results. In the solutions that the student participants proposed in this thesis, for example, many included electro-mechanical elements like motors, and sensors which would require electrical power sources like batteries, or connections to the power grid. Thinking of the electrical domain, novice engineering designers and pre-university students could perhaps be expected to have relatively less knowledge (factual, conceptual, and procedural) of the electrical domain than of the mechanical domain. While they may have awareness of common concepts like electric motors, the bulk of the factual and conceptual knowledge of the electrical engineering domain may be less accessible to pre-university students, especially as the electronics industry proceeds towards tighter integration of components, miniaturization, and a relatively high difficulty of repair. It is unknown what novice designers in the electrical engineering domain may exhibit as far as design behaviours given a lower expected level of knowledge of the domain. Other domains like chemical engineering, which are even farther removed from peoples' everyday experiences, would also be interesting to investigate. It is also interesting to think about multi-disciplinary problem domains; in this thesis, the students occasionally came up with electro-mechanical solutions to the design prompts, and they typically struggled once their solutions transitioned out of the purely mechanical domain. As multi-disciplinary engineering programs like mechatronics engineering increase in prevalence, these programs are a natural site to extend this work.

Other variables which were controlled in this experiment could be changed, or relaxed. For example, the problems posed to the student participants could be considered as an adaptive design problem (Pahl, et al., 1984), or perhaps a variant design problem in the case of the jar opening problem, as these devices already exist in many forms. If instead of these problems, a more open problem– or even a wicked problem – could be posed to students where there is more opportunity for students to produce original designs. The prompt could even ask students to prioritize novelty or be framed as starting a new entrepreneurial venture instead of a new design for a co-op employer at an existing company. It is unknown what the increased challenge of emphasizing innovative solutions or posing more open problem domains would have on novice design behaviours. The design activity could also be lengthened, perhaps to promote the use of design tools like CAD – students could even be promoted to use these tools as part of the problem statement.

This thesis presented data on the knowledge and epistemological changes after students participated in a four-month long co-op work term. There was evidence of new knowledge domains, and development of existing knowledge from these experiences, but this did not manifest in observable development in personal epistemologies, or observable changes in the 1B design activity. As Litster et al. (2021) point out, there has been exceedingly little research into students' experiences of design in the work-integrated learning environment, and unfortunately, this thesis leaves more questions than answers. Future work could use a similar research design to this study but could instead focus more on the experiences and impacts of the co-operative work terms on novice designers. A longer-term longitudinal study, for example, could follow students as they experience multiple work terms and attempt to assess what their experiences included, and how that has changed their design behaviours.

It was never mentioned explicitly, but as students described how they would justify their choices to their boss, or when they were discussing disagreements they had with the ME 100 teaching team, some of the comments came across as deference not because the students seemed to have a dichotomous view of knowledge where correctness was dictated by experts (i.e. their boss), but perhaps deference out of respect for the more senior member of the company, lack of confidence in one's position, or perhaps even to a perceived lack of power to speak up and/or defend your ideas. There is growing research in evaluating the social climate in engineering teams in the curricular environment (Kerr, et al., 2023), including explicitly promoting undergraduate students' psychological safety in team environments (Payne & Hanson, 2023). It is possible that a lack of psychological safety, especially in interactions with superiors (either in the classroom, or outside) could have a chilling effect on personal epistemological development; however, more research is needed in this space.

As stated previously, the approach of assessing personal epistemological development through a realistic design task is a novel approach that would benefit from additional use/validation. This method shows great promise as a means of assessing personal epistemology and with more testing could be a useful diagnosis tool in both teaching and research contexts. For example, this approach could be used in a teaching environment to tailor training to individual students to increase the effectiveness of the teaching and learning environment; or could be used to assess and identify the most efficient teaching strategies for promoting student development in design. This future work could also experiment with shorter design activities, or simpler design prompts to see if similar assessments of personal epistemology and design behaviour can be made. With a shorter protocol, fatigue would be less of an issue, and the sample size could be increased to seek more generalizable findings. It would also be useful to attempt this protocol in other settings, for example the K-12 education sector. Coding and STEM learning were added to the Ontario school curriculum in 2022 (Government of Ontario, 2022), and this approach could be useful to schoolteachers to assist with diagnosing student performance in engineering design. Before this would be possible, this protocol would need to be tested with pre-novice designers. For example, is there a minimum amount of domain knowledge needed before personal epistemology can be reliably assessed?

Lastly, targeted investigation into the causes behind regression of personal epistemology in the design context would be useful to identify the elements of the teaching and learning environment which are not helpful, or which are actively harmful, to individual development. Several participants in this thesis regressed in their level of personal epistemology between the 1A and 1B interviews, even though they were participating in projects in ME 100 which should promote epistemological development, and in some cases, had relevant co-op work terms in industry environments prior to their second interview.

11.4 Summary

This thesis revealed connections between experiences and student knowledge, personal epistemology, and design behaviours. In tracking the students longitudinally, this thesis found that personal epistemology and knowledge developed in different ways, and at different times. The students were able to develop both breadth and depth of knowledge and demonstrated more informed design behaviours in the second interview, even though most students did not develop their personal epistemologies.

The methods and techniques employed to understand student knowledge and personal epistemology were novel approaches which show promise for future research. This thesis measured personal epistemological development in situ as students solved design problems; an approach which may be more efficient, and more accurate in measuring personal epistemology in the context of engineering design.

References

Adams, R. S., Turns, J. & Atman, C. J., 2003. Educating effective engineering designers: the role of reflective practice. *Design Studies*, 24(3), pp. 275-294.

Amabile, T. M., 1996. *Creativity in Context.* Boulder, CO: Westview Press.

Ambrose, S. et al., 2010. In: *How Learning Works: Seven Research-Based Principles for Smart Teaching.* San Francisco: John Wiley & Sons, Inc, pp. 103-120.

Anderson, L. W. et al. eds., 2001. *A Taxonomy for Learning, Teaching, and Assessing.* Abridged ed. New York: Addison Wesley.

Associate Provost, Co-operative and Experiential Education, n.d. *University of Waterloo.* [Online] Available at: https://uwaterloo.ca/associate-provost-co-operative-and-experiential-education/about/our-history
[Accessed 6 August 2024].

Atman, C., 2024. *Design Signatures.* [Online]
Available at: https://www.designsignatures.org/teaching-resources/teaching-resources-home
[Accessed 29 January 2025].

Atman, C. J., 2019. Design Timelines: Concrete and sticky representations of design process expertise. *Design Studies,* 65(C), pp. 125-151.

Atman, C. J. & Bursic, K. M., 1996. Teaching engineering design: Can reading a Textbook Make a Difference?. *Research in Engineering Design,* 8(4), pp. 240-250.

Atman, C. J. & Bursic, K. M., 1998. Verbal Protocol Analysis as a Method to Document Engineering Student Design Processes. *Journal of Engineering Education,* 87(2), pp. 121-132.

Atman, C. J., Cardella, M. E., Turns, J. & Adams, R., 2005. Comparing freshman and senior engineering design processes: an in-depth follow-up study. *Design Studies,* 26(4), pp. 325-357.

Atman, C. J., Chimka, J. R., Bursic, K. M. & Nachtmann, H. L., 1999. A comparison of freshman and senior engineering design processes. *Design Studies*, 20(2), pp. 131-152.

Baer, J. & Kaufman, J., 2005. Bridging generality and specificity: The amusement park theoretical (APT) model of creativity. *Roeper Review,* 27(3), pp. 158-163.

Bernhard, J., Carstensen, A.-K., Davidsen, J. & Ryberg, T., 2019. Practical Epistemic Cognition in a Design Project—Engineering Students Developing Epistemic Fluency. *IEEE Transactions on Education,* 62(3), pp. 216-225.

Brown, J. S., Collins, A. & Duguid, P., 1989. Situated Cognition and the Culture of Learning. *Educational Researcher,* 18(1), pp. 32-42.

Brown, S., Montfort, D. & Frye, N., 2013. *What is Engineering Knowledge: A Longitudinal Study of Conceptual Change and Epistemology of Engineering Students and Practitioners.* Atlanta, GA, ASEE Annual Conference and Exposition.

Budinoff, H. D. & Subbian, V., 2021. *Asset-based Approaches to Engineering Design Education: A Scoping Review of Theory and Practice.* Online, ASEE Annual Conference.

Budinoff, H., Subbian, V. & Lopez, F., 2022. *Integrating Asset-based Practices into Engineering Design Instruction.* Minneapolis, ASEE Annual Conference and Exposition.

Carberry, A. R., Lee, H.-S. & Ohland, M. W., 2010. Measuring Engineering Design Self-Efficacy. *Journal of Engineering Education*, 99(1), pp. 71-79.

Chance, S. M. et al., 2019. Guest Editorial Special Issue on Using Enquiry- and Design-Based Learning to Spur Epistemological and Identity Development of Engineering Students. *IEEE Transactions on Education,* 62(3), pp. 157-164.

College Board, 2020. *AP Computer Science A: Course and Exam Description.* [Online]
Available at: https://apcentral.collegeboard.org/media/pdf/ap-computer-science-a-course-and-exam-description.pdf
[Accessed 4 December 2023].

Creswell, J. & Creswell, J., 2018. *Research Design: Qualitative, Quantitative, and Mixed Methods.* 5th ed. Los Angeles: Sage.

Creswell, J. W. & Poth, C. N., 2018. *Qualitative Inquiry & Research Design: Choosing Among Five Approaches.* 4th ed. Thousand Oaks, CA: Sage.

Crismond, D. P. & Adams, R. S., 2012. The Informed Design Teaching and Learning Matrix. *Journal of Engineering Education,* 101(4), pp. 738-797.

Cross, N., 1990. The nature and nurture of design ability. *Design Studies,* 11(3), pp. 127-140.

Cross, N., 2011. *Design Thinking.* London: Bloomsbury Academic.

Cross, N., 2018. Expertise in Professional Design. In: K. A. Ericsson, R. R. Hoffman, A. Kozbelt & A. M. Williams, eds. *The Cambridge Handbook of Expertise and Expert Performance, 2nd ed.* Cambridge: Cambridge University Press, pp. 373-388.

Design Council, 2019. *Framework for Innovation: Design Council's evolved Double Diamond.* [Online]
Available at: https://www.designcouncil.org.uk/our-work/skills-learning/tools-frameworks/framework-for-innovation-design-councils-evolved-double-diamond/
[Accessed 30 January 2023].

Dorst, K., 2011. The core of 'design thinking' and its application. *Design Studies*, 32(6), pp. 521-532.

Dorst, K., 2019. Co-evolution and emergence in design. *Design Studies,* Volume 65, pp. 60-77.

Dorst, K. & Cross, N., 2001. Creativity in the Design Process: Co-evolution of problem-solution. *Design Studies,* 22(5), pp. 425-437.

Ebbinghaus, H., (Trans.) Ruger, H. A. & (Trans.) Bussenius, C. E., 1913. *Memory: A Contribution to Experimental Psychology.* New York: Teachers College Press.

Elo, S. & Kyngas, H., 2008. The qualitative content analysis process. *Journal of Advanced Nursing,* 62(15), pp. 107-115.

Engineers Canada, 2016. *Graduate Attributes.* [Online]
Available at: https://engineerscanada.ca/sites/default/files/Graduate-Attributes.pdf
[Accessed 29 January 2021].

Ericsson, K. A., 2003. The Acquisition of Expert Performance as Problem Solving. In: J. E. Davidson & R. J. Sternberg, eds. *The Psychology of Problem Solving.* Cambridge: Cambridge University Press, pp. 31-86.

Ericsson, K. A. & Simon, H. A., 1996. *Protocol Analysis: Verbal Reports as Data, Revised Edition.* Cambridge, MA: The MIT Press.

Felder, R. M. & Brent, R., 2004. The Intellectual Development of Science and Engineering Students. Part 1: Models and Challenges. *Journal of Engineering Education,* 93(4), pp. 269-277.

Felder, R. M. & Brent, R., 2004. The Intellectual Development of Science and Engineering Students. Part 2: Teaching to Promote Growth. *Journal of Engineering Education,* 93(4), pp. 279-291.

Feltovich, P. J., Prietula, M. J. & Ericsson, K. A., 2018. Studies of Expertise from Psychological Perspectives: Historical Foundations and Recurrent Themes. In: K. A. Ericsson, R. R. Hoffman, A. Kozbelt & A. M. Williams, eds. *Cambridge Handbook of Expertise and Expert Performance.* 2nd ed. Cambridge: Cambridge University Press, pp. 59-83.

Feucht, F. C., 2010. Epistemic Climate in Elementary Classrooms. In: L. D. Bendixen & F. C. Feucht, eds. *Personal Epistemology in the Classroom.* Cambridge: Cambridge University Press, pp. 55-94.

FIRST, 2024. *FIRST Robotics Competition.* [Online]
Available at: https://www.firstinspires.org/robotics/frc
[Accessed 9 August 2024].

Frise, P., Rohrauer, G., Minaker, B. & Altenhof, W., 2003. *Identifying the Design Engineering Body of Knowledge.* Stockholm, International Conference on Engineering Design.

Gama, K., 2017. *Preliminary Findings on Software Engineering Practices in Civic Hackathons.* s.l., s.n.

Gero, J. S. & Kannengiesser, U., 2004. The situated function–behaviour–. *Design Studies,* 25(4), pp. 373-391.

Gero, J. S. & McNeill, T., 1998. An Approach to the Analysis of Design Protocols. *Design Studies,* 19(1), pp. 21-61.

Glass, R. L., 1997. *Software Runaways: Monumental Software Disasters.* 1st ed. s.l.:Prentice Hall.

Goldman, S. L., 2004. Why we need a philosophy of engineering: A work in progress. *Interdisciplinary Science Reviews,* 29(2), pp. 163-176.

Government of Ontario, 2022. *Ontario Modernizing School Science Curriculum.* [Online]
Available at: https://news.ontario.ca/en/release/1001722/ontario-modernizing-school-science-curriculum
[Accessed 8 January 2025].

Green, D. & Southard, M. Z., 2018. *Perry's Chemical Engineers' Handbook.* 9th ed. New York: McGraw-Hill Education.

Hodges, C. et al., 2020. *The Difference Between Emergency Remote Teaching and Online Learning.* [Online]
Available at: https://er.educause.edu/articles/2020/3/the-difference-between-emergency-remote-teaching-and-online-learning
[Accessed 6 March 2021].

Hofer, B. K., 2020. Epistemic Cognition: Why It Matters for an Educated Citizenry and What Instructors Can Do. *New Directions for Teaching and Learning,* 2020(164), pp. 85-94.

Hofer, B. K. & Bendixen, L. D., 2012. Chapter 9 Personal Epistemology: Theory, Research, and Future Directions. In: K. R. Harris, S. Graham & T. Urdan, eds. *APA Educational Psychology Handbook: Vol. 1. Theories, Constructs, and Critical Issues.* s.l.:American Psychological Association, pp. 227-256.

Hoffman, R. R. et al., 2014. The Nature of Proficiency. In: *Accelerated Expertise.* New York: Psychology Press, pp. 17-31.

Horowitz, P. & Hill, W., 2015. *The Art of Electronics.* 3rd ed. Cambridge: Cambridge University Press.

Howard, T., Culley, S. & Dekoninck, E., 2008. Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies,* 29(2), pp. 160-180.

Howard, T., Culley, S. & Dekoninck, E., 2008. Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies,* 29(2), pp. 160-180.

Jehng, J.-C. J., Johnson, S. D. & Anderson, R. C., 1993. Schooling and Students' Epistemological Beliefs About Learning. *Contemporary Educational Psychology,* 18(1), pp. 23-35.

Jonassen, D. H., 2000. Toward a Design Theory of Problem Solving. *Educational Technology Research and Development,* 48(4), pp. 63-85.

Jonassen, D. H., 2011. *Learning to Solve Problems: A Handbook for Designing Problem-Solving Learning Environments.* New York: Routledge.

Kahneman, D., 2011. *Thinking, Fast and Slow.* New York: Farrar, Straus, and Giroux.

Kerr, V., Sheridan, P. K. & Moore, E., 2023. *A Socio-Emotional Framework to Understand Engagement in Engineering-Student Project-Teams.* Kelowna, CEEA-ACEG Annual Conference.

King, P. & Kitchener, K. S., 1994. *Developing Reflective Judgement.* San Francisco: Jossey-Bass.

Lawson, B. & Dorst, K., 2009. *Design Expertise.* Abingdon: Routledge.

Litster, G. & Hurst, A., 2021. Protocol Analysis in Engineering Design Education Research: Observations, Limitations, and Opportunities. *Studies in Engineering Education,* 1(2), pp. 14-30.

Litster, G., Hurst, A. & Pretti, J. T., 2021. *Surveying Design Skill Development in Work-Integrated Learning Experiences: A Review of the Literature.* Gothenburg, International Conference on Engineering Design, ICED21.

Long, M., 2014. *Hack@Brown.* [Online]
Available at: https://medium.com/hack-at-brown/redesigning-the-hackathon-experience-for-beginners-5220c508e96f
[Accessed 11 Sept 2023].

Marra, R. M., Palmer, B. & Litzinger, T. A., 2000. The Effects of a First-Year EngineeringDesign Course on Student IntellectualDevelopment as Measured by the PerryScheme. *Journal of Engineering Education,* 89(1), pp. 39-45.

Massachusetts Department of Elementary and Secondary Education, 2020. *Science, Technology, Engineering, and Mathematics (STEM).* [Online]

Available at: https://www.doe.mass.edu/stem/ste/?section=classroom [Accessed February 2021].

McConnell, S., 2004. *Code Complete.* Second ed. Redmond, WA: Microsoft Press.

Miles, M. B., Huberman, A. M. & Saldana, J., 2020. *Qualitative Data Analysis: A Methods Sourcebook.* 4th ed. Thousand Oaks: Sage Publications.

Montfort, D., Brown, S. & Shinew, D., 2014. The Personal Epistemologies of Civil Engineering Faculty. *Journal of Engineering Education,* 103(3), pp. 388-416.

Moraes, C., Blain-Moraes, S., Morell-Tomassoni, S. & Gorbet, R. B., 2019. The W-model: a pre-college design pedagogy for solving. *International Journal of Technology and Design Education,* Volume 31, pp. 139-164.

Mosier, K., Fischer, U., Hoffman, R. R. & Klein, G., 2018. Expert Professional Judgments and "Naturalistic Decision Making". In: K. A. Ericsson, R. R. Hoffman, A. Kozbelt & A. M. Williams, eds. *The Cambridge Handbook of Expertise and Expert Performance, 2nd ed.* Cambridge: Cambridge University Press, pp. 453-475.

Mullins, C. A., Atman, C. J. & Shuman, L. J., 1999. Freshman Engineers' Performance When Solving Design Problems. *IEEE Transactions on Education,* 42(4), pp. 281-288.

Nickel, J. et al., 2024. *Student Perceptions and Attitudes Towards Engineering Design in Work-Integrated Learning Contexts.* Portland, ASEE Annual Conference and Exposition.

Nickel, J. et al., 2023. *A Qualitative Investigation of Undergraduate Students' Design Experiences in a Work-Integrated Learning Setting.* Bordeaux, s.n.

Noble, D. F., 1977. *America by Design.* Oxford: Oxford University Press.

Pahl, G., Beitz, W. & Wallace, K., 1984. *Engineering Design.* London: Design Council.

Paulsen, M. B. & Wells, C. T., 1998. Domain Differences in the Epistemological Beliefs of College Students. *Research in Higher Education,* 39(4), pp. 365-384.

Pavelich, M. J. & Moore, W. S., 1996. Measuring the Effect of Experiential Education Using the Perry Model. *Journal of Engineering Education,* 85(4), pp. 287-292.

Payne, M. M. & Hanson, J. H., 2023. *Teaching Students Skills to Foster Psychological Safety in a Team Environment.* Baltimore, ASEE Annual Conference and Exposition.

Perry, W. G., 1970. *Forms of Intellectual and Ethical Development in the College Years: A Scheme.* San Francisco: Jossey-Bass.

Pretz, J. E., Naples, A. J. & Sternberg, R. J., 2003. Recognizing, Defining, and Representing Problems. In: J. E. Davidson & R. J. Sternberg, eds. *The psychology of Problem Solving.* Cambridge: Cambridge University Press, pp. 3-30.

Prince, M., 2004. Does Active Learning Work? A Review of the Research. *Journal of Engineering Education,* 93(3), pp. 223-231.

Rennick, C., Hulls, C. C. & Gryguc, A., 2021. *Assessing the Impact of Transitioning Introductory Design Instruction to an Online Environment.* Online, ASEE Virtual Annual Conference.

Rennick, C., Hulls, C. C. & McKay, K. N., 2019. Introductory Engineering Decision-Making: Guiding First-Year Students to Relativism in Software Design. *IEEE Transactions on Education,* 62(3), pp. 199-208.

Rennick, C., Lenover, M., Li, E. & Bedi, S., 2022. *Co-Designing Design Activities with Undergraduate Students.* Minneapolis, ASEE Annual Conference and Exposition'.

Rennick, C. et al., 2022. Characterizing Engineering Design Activities Using Jonassen's Design Theory of Problem Solving. *International Journal of Engineering Education,* 38(1), pp. 1-11.

Rennick, C. & McKay, K., 2018. *Componential Theories of Creativity: A Case Study of Teaching Creative Problem Solving.* Vancouver, CEEA-ACEG Annual Conference.

Rule, D. C. & Bendixen, L. D., 2010. The Integrative Model of Personal Epistemology Development: Theoretical Underpinnings and Implications for Education. In: L. D. Bendixen & F. C. Feucht, eds. *Personal Epistemology in the Classroom.* Cambridge: Cambridge University Press, pp. 94-124.

Runco, M. & Chand, I., 1995. Cognition and Creativity. *Educational Psychology Review*, 7(3), pp. 243-267.

Schommer, M., 1990. Effects of Beliefs About the Nature of Knowledge on Comprehension. *Journal of Educational Psychology,* 82(3), pp. 498-504.

Schon, D. A., 1983. *The Reflective Practitioner: How Professionals Think in Action.* s.l.:Basic Books, Inc.

Shad Canada, 2019. *Shad Canada.* [Online]
Available at: https://www.shad.ca/about-shad/
[Accessed 30 January 2023].

Shealy, T., Gero, J., Ignacio, P. & Song, I., 2023. *Changes in Cognition and Neurocognition when Thinking Aloud During Design.* Bourdeaux, Design Society.

Sheppard, S. D., Macatangay, K., Colby, A. & Sullivan, W. M., 2009. *Educating Engineers: Designing for the future of the field.* San Francisco: Jossey-Bass.

Simon, H. A., 1996. *The Sciences of the Artificial.* 3rd ed. Cambridge, MA: The MIT Press.

Skills Ontario, 2019. *Mechanical CAD.* [Online]
Available at: https://www.skillsontario.com/files/www/2019_Scopes/2019_Scope_-_S_-_Mechanical_CAD.pdf
[Accessed 20 March 2023].

Tang, H., Lee, Y. & Gero, J., 2011. Comparing collaborative co-located and distributed design processes in digital and traditional sketching environments: A protocol study using the function–behaviour–structure coding scheme. *Design Studies,* 32(1), pp. 1-29.

Technovation Girls, 2023. [Online]
Available at: https://technovationchallenge.org/
[Accessed April 2023].

Thomas, J. C. & Carroll, J. M., 1979. The Psychological Study of Design. *Design Studies,* 1(1), pp. 5-11.

Vieira, S. L. d. S. et al., 2019. *Comparing the Design Nurocognition of Mechanical Engineers and Architects: A Study of the Effect of Designer's Domain.* Delft, International Conference on Engineering Design (ICED19).

Weisberg, R. W., 2018. Expertise and Structured Imagination in Creative Thinking: Reconsideration of an Old Question. In: K. A. Ericsson, R. R. Hoffman, A. Kozbelt & A. M.

Williams, eds. *Cambridge Handbook of Expertise and Expert Performance.* Cambridge: Cambridge University Press, pp. 812-834.

Wertz, R. E., Purzer, S., Fosmire, M. J. & Cardella, M. E., 2013. Assessing Information Literacy SkillsDemonstrated in an Engineering Design Task. *Journal of Engineering Education,* 102(4), pp. 577-602.

Wise, J. et al., 2001. *Measuring Cognitive Growth in Engineering Undergraduates: A Longitudinal Study.* Albuquerque, NM, ASEE Annual Conference and Exposition.

Wood, K. L. et al., 2012. *A Symphony of Designiettes: Exploring the Boundaries of Design Thinking in Engineering Education.* San Antoni0, s.n.

Yin, R. K., 2018. *Case Study Research and Applications : Design and Methods.* 6th ed. s.l.:SAGE Publications.

Zhu, J. et al., 2019. Engineering Students' Epistemological Thinking in the Context of Project-Based Learning. *IEEE Transactions on Education,* 62(3), pp. 188-198.

Appendix A Interview Protocol – Student Participants

Note: This protocol is approved by the University of Waterloo, Office of Research Ethics, ORE #43656

1A Demographic Questions:

1. To protect your identity, a pseudonym will be used to identify your data, and in any future publications. Would you like to select your own pseudonym?
    a. ***If consent was given for quotations***: Would you prefer this pseudonym is used for any direct quotations I use? Or would you like them to appear anonymously?
2. What gender do you identify with? If you would prefer not to say, that is ok too.
3. Where did you attend school before the University of Waterloo?
    a. Was there anything in your past schooling that you feel really prepared you for engineering?

1A Experience Questions:

1. Tell me a bit about yourself.
    a. What hobbies do you enjoy doing?
    b. What sorts of extra-curriculars or work experiences did you have before joining Waterloo?
    c. Have you started any entrepreneurial initiatives?
    d. Are there any engineers or designers in your family?
2. Tell me about why you selected your program?
    a. What are you hoping to gain from your program?
3. Have you participated in any organized design activities? (First Robotics, hackathons, Shad Valley, etc.)
    a. Was there a structure to the process you went through?
    b. Were there mentors/instructors helping guide your work? What was their background?
    c. Can you clarify your contributions to the work you described? How long did you work on it? How many people were you working with? Which aspects did you work on?
    d. During these experiences, was it ever unclear to you what the actual problem was that you were solving? How did you resolve that uncertainty? Can you explain?
    e. During these experiences, did you feel there was room for you to be creative? Can you explain?
    f. During these experiences, how did you know when you had found the right solution?
    g. Did you also build your solution to the problem?
    h. What did you learn from these experiences about how to design?
4. Did you have any design experiences in prior classes, student clubs, or organized groups outside of school? What were you designing?
    a. Was there a structure to the process you went through?
    b. Were there mentors/instructors or others helping guide your work? What was their background?

c. Can you clarify your contributions to the work you described? How long did you work on it? How many people were you working with? Which aspects did you work on?
d. During these experiences, was it ever unclear to you what the actual problem was that you were solving? How did you resolve that uncertainty? Can you explain?
e. During these experiences, did you feel there was room for you to be creative? Can you explain?
f. During these experiences, how did you know when you had found the right solution?
g. Did you also build your solution to the problem?
h. What did you learn from these experiences about how to design?

5. What sorts of other design and build experiences did you have before attending Waterloo? This could be on your own, or with friends.
    a. Were there mentors or others helping guide your work? What was their background?
    b. Can you clarify your contributions to the work you described? How long did you work on it? How many people were you working with? Which aspects did you work on?
    c. During these experiences, was it ever unclear to you what the actual problem was that you were solving? How did you resolve that uncertainty? Can you explain?
    d. During these experiences, did you feel there was room for you to be creative? Can you explain?
    e. During these experiences, how did you know when you had found the right solution?
    f. Did you also build your solution to the problem?
    g. What did you learn from these experiences about how to design?
6. Is there anything else you want to add before we move on to the design problem?

1B Experience Questions:

1. When your friends/family ask you about your studies, how do you describe what engineering is to them?
2. During your last academic term, were you presented with any problems where you didn't know everything you needed to know to solve the problem? Tell me about it. How did you solve it?
3. During your last term, did you face any situations where the problem you were working on had unclear goals or instructions?
    a. What role did your instructor/classmates play in navigating this? Did you ever disagree with their advice? Tell me about it.
    b. How did you know you had solved the problem?
4. In your 1A term, were there any courses where you were taught design?
    a. Would you say that ME 100 was different from your other courses in 1A? If so, how?
    b. How was design taught in those courses? Lectures? Design activities?
    c. Did you have an opportunity to practice designing in 1A?
        i. Was there a structure to the design process you went through? Can you describe it?
        ii. Were there mentors/instructors helping guide your work? What was their background?
        iii. Can you clarify your contributions to the work you described? How long did you work on it? How many people were you working with? Which aspects did you work on?

    iv. During these experiences, was it ever unclear to you what the actual problem was that you were solving? How did you resolve that uncertainty? Can you explain?
    v. During these experiences, did you feel there was room for you to be creative? Can you explain?
    vi. During these experiences, how did you know when you had found the right solution?
    vii. Did you also build your solution to the problem?
    viii. What did you learn from these experiences about how to design?

5. While you have been at university, have you participated in any student teams or other organized groups at the university?
    a. What were you working on?
    b. Would you characterize any of your time with that team/group as design?
        i. Was there a structure to the process you went through?
        ii. Can you clarify your contributions to the work you described? How long did you work on it? How many people were you working with? Which aspects did you work on?
        iii. Did you also build your solution to the problem?
        iv. What did you learn from these experiences about how to design?
    c. Were there mentors/instructors or others helping guide your work? What was their background?
    d. During these experiences, was it ever unclear to you what the actual problem was that you were solving? How did you resolve that uncertainty? Can you explain?
    e. During these experiences, did you feel there was room for you to be creative? Can you explain?
    f. During these experiences, how did you know when you had found the right solution?
6. Since we last spoke, have you participated in any organized design activities? (e.g., Hackathons)
    a. Was there a structure to the process you went through?
    b. Were there mentors/instructors helping guide your work? What was their background?
    c. Can you clarify your contributions to the work you described? How long did you work on it? How many people were you working with? Which aspects did you work on?
    d. During these experiences, was it ever unclear to you what the actual problem was that you were solving? How did you resolve that uncertainty? Can you explain?
    e. During these experiences, did you feel there was room for you to be creative? Can you explain?
    f. During these experiences, how did you know when you had found the right solution?
    g. Did you also build your solution to the problem?
    h. What did you learn from these experiences about how to design?
7. Since we last spoke, have you designed anything by yourself, like a side project?
    a. What were you working on?
    b. Was there a structure to the process you went through?
    c. During these experiences, was it ever unclear to you what the actual problem was that you were solving? How did you resolve that uncertainty? Can you explain?
    d. While working on this, how did you know when you had found the right solution?

    e. Did you also build your solution to the problem?
    f. What did you learn from these experiences about how to design?
8. For 4-stream students coming back from their first work term:
    a. Tell me about your coop placement. Where did you work and what kind of work were you doing?
    b. Did you apply any of the design skills/knowledge that you learned in 1A while in your coop job?
        i. Which skills/knowledge are you thinking of?
        ii. How did you use that knowledge in your position?
    c. What were the top 3 or 4 things you learned during the work term?
    d. During your work term, did you face any situations where you didn't know everything you needed to know to solve the problem? Tell me about it.
    e. During your work term, did you face any situations where the problem you were working on had unclear goals or instructions?
        i. What role did your manager/co-workers play in navigating this? Did you ever disagree with him/her? Tell me about it.
        ii. How did you know you had solved the problem?
    f. Would you consider any of your experiences on your coop term as design? Tell me about them. What sorts of tasks were you responsible for?
        i. How much of the design cycle were you able to experience? Did you get a chance to implement your design?
        ii. Was there a structured process you had to follow? Did you conduct a design review with a supervisor?
9. Has your perspective of what engineering "is" changed since you started at Waterloo? If so, how?
    a. What impact did your instructors have on that perspective?
    b. What impact did your peers have?
10. How have you changed or grown since I last met with you?
11. Is there anything else you want to add before we move on to the design problem?

Protocol Analysis Practice:

In this experiment, I am interested in what you think about when you are developing a solution to a design problem. In order to do this, I am going to ask you to think aloud as you work on the problem I give you. What I mean by think aloud is that I want you to tell me everything you are thinking from the time you first see the question until your final answer is finished. I would like you to talk aloud constantly from the time I present the problem until you have finished designing your solution. I don't want you to try to plan out what you say or try to explain to me what you are saying. Just act as if you are alone in the room speaking to yourself. It is most important that you keep talking. If you are silent for any long period of time, I will ask you to talk. Do you understand what I am asking you to do?

Good, now we will begin with some practice problems. First, I want you to multiply these two numbers in your head and tell me what you are thinking as you get an answer: “What is the result of multiplying 24 x 36”?

Good, now I want to see how much you can remember about what you were thinking from the time you read the question until you gave the answer. I am interested in what you can actually remember rather than what you thinking you must have thought. If possible, I would like you to tell about your memories in the sequence in which they occurred while working on the problem. Please tell me if you are uncertain about any of your memories. I don’t want you to work on solving the problem again, just report all that you can remember thinking about when answering the question. Now tell me what you remember.

Good. Now I will give you one more practice problem before we proceed with the main experiment. I want you to do the same thing for this problem. I want you to think aloud as before as you think about the question, and after you have answered it I will ask you to report all that you can remember about your thinking. Any questions? Here is your next problem:
“How many windows are there in your parent’s house”?

Now tell me all that you can remember about your thinking.

Protocol Analysis Main Problem:

Good. Now we will move to the main experiment. This problem will ask you to design something to solve a problem, and you will have up to 90 minutes to complete your design. I want you to do the same thing for this problem as you did for the practice problems: please think aloud as you think about the question, and after you have answered it, I will ask you to report all that you can remember about your thinking. I will ask you to share your screen so that I can record any work you are doing on your computer. Feel free to use paper to sketch or jot down ideas as well. Any questions before we get started?

1A design task (Fall 2021): Welcome to your first day working for the Waterloo Kitchen Supply Company. Here at WKSC, we pride ourselves on our ability to design products for every user. As our newest employee, we would like you to propose a new product that addresses a problem our users have reported. We would like you to propose the design of a device that enables people with disabilities to open jars with screw-on lids using only one hand.

Please explain your solution as clearly and completely as possible. Someone should be able to build the device from your solution without any questions. Feel free to search the internet for any missing information you might need.

1B design task (Winter/Spring 2022): Welcome to your new position with Waterloo Region Windows and Doors. In our client research, we have identified a business opportunity for a new product. I would like you to design a device to help disabled users open a stuck double-hung window.

Please explain your solution as clearly and completely as possible. Someone should be able to build the device from your solution without any questions. Feel free to search the internet for any missing information you might need.

Retrospective Report:

Thank you for all your effort in creating a solution to the problem. If you consent to share them with me, can you hold any paper you were writing on up to the camera so I can capture your work?

1. At the beginning of the activity, did you feel like there was missing information in the instructions about what you had to deliver (***vs. the how)***?
    a. How did you know you had resolved the issue?
2. At the beginning of the activity, did you feel like it was unclear how you were meant to proceed?
    a. How did you know you had resolved the issue?
3. Can you summarize the design process you just went through?
    a. Is there more than one approach to solving the problem?
4. Did you apply any of the design skills/knowledge that you learned in 1A while solving the problem?
    a. Which skills/knowledge are you thinking of?
    b. What do you wish you had been taught during the term? (Both how to design, and knowledge relevant to implementing the project)
5. **4-Stream students only:** Did you apply any of the design skills/knowledge that you learned in your first work term while solving the problem?
    a. Which skills/knowledge are you thinking of?
6. Is there more than one solution to this problem?
    a. How did you know you had found the right solution to the problem?
7. Have you experienced a problem like this before? Did you solve it the same way?
8. Can you talk more about the different decisions you made during the activity?
    a. Which decisions can you identify?
    b. How did you know you made the right decision?
    c. [pick one] How would you justify this decision to your boss?
9. What would you do differently next time?
10. Before we end things, is there anything else you want to say?

Appendix B Interview Protocol – Instructor Participants

Note: This protocol is approved by the University of Waterloo Office of Research Ethics, ORE #43656

Opening:

Hi, I'm Chris Rennick and I am a PhD student in the department of Management Sciences. I am studying the growth of engineering students as they move through the first year of their studies. I have some questions to ask about how *design* was taught and assessed in 1A that will take approximately 45 minutes, and I will be recording this interview. These questions will ask you about the class as a whole, and not individual students.

1. To start things off, have you had a chance to read the information letter? Feel free to take a minute and read it now, if you have not. Do you have any questions?

Consent:

Do you agree to participate in this study knowing that you are being recorded and that you can withdraw at any point with no consequences to you?

Questions:

1. Can you tell me a little about your course? How did it go this term?

I am going to ask some questions about where and how design was taught in ME 100. The first section of this interview will focus on your role as the instructor, the second section will focus on the role of students as learners in the course, and the final section will ask about your general approach to teaching ME 100.

1. How do you typically describe what engineering design "is" to your first-year students?
2. How was design taught in the lecture(s)?
    a. What design tools were taught to students? (CAD, ideation, decision-making, etc.)
        i. For each tool you mentioned, how did you communicate the role of that tool in the design process? For example, CAD could be used for conceptual design, detailed design, and/or communication of final designs.
    b. Did you explicitly teach the design process in your course? What did this process look like? How was it taught?
    c. What formal design methods were taught to students?
3. At any point in the course, did you conduct design live with students?
    a. What kind(s) of problems were you solving with them?
    b. What role did you play in this design session?
    c. How much of the design process did you model for students?

4. Are there other course resources which students are expected to engage in? (e.g., textbooks)
5. What knowledge of mechanical engineering are you expecting students to obtain in ME 100?
6. What skills of the domain are you expecting students to develop/obtain in ME 100?
7. Is there any engineering “know-how” that you teach to students in ME 100?

Let’s turn our attention to the role of students as learners in the course:

1. Did students do any live designing where members of the teaching team were present?
    a. What problem(s) were students solving?
        i. Did the problem have more than one solution?
        ii. How were success criteria defined for the project? (student selected vs. assigned? Incentivized? Assessed?)
        iii. Would you consider the problem(s) ill-structured? Can you explain?
        iv. Would you consider the problem(s) complex? Can you explain?
    b. Were students expected to apply a design process that was taught to them?
    c. What was the role of the teaching team during the live session?
    d. Was the experience formative or summative?
    e. What social interactions did students have with their peers during this exercise?
2. I would like to talk about any design projects which students participated in during the term:
    a. Can you quickly summarize the project?
    b. Were the problems assigned or open for students to select?
        i. Did the problem have more than one solution?
        ii. How were success criteria defined for the project? (student selected vs. assigned? Incentivized? Assessed?)
        iii. Would you consider the problem(s) ill-structured? Can you explain?
        iv. Would you consider the problem(s) complex? Can you explain?
    c. What sorts of learning supports were provided by the teaching team?
        i. Were students expected to apply structured methods that were taught in the course?
    d. How were they assessed?
3. Are there other ways that design (or related topics) was taught, or other ways that students learned design (or related topics) in your course this term?

The final section of the interview will focus on your teaching philosophy in ME 100.

1. In your view, what is the purpose of ME 100 to the broader curriculum?
2. Is your role of instructor different in ME 100 compare to other courses you teach? If so, how?
3. Is engineering design an objective or subjective domain? Do students agree?
4. Before we end things, is there anything else you want to add?

Appendix C Detailed Data – Pre-university Experiences

MJ

MJ is a male student who completed his high school in western Canada. He completed an IB program there which he felt helped to develop his time management skills due to the workload of the program. He described himself as having few hobbies (which included watching movies and playing the guitar and piano) and being focused on academics. He had a couple different summer jobs in the years prior to enrolling at Waterloo. MJ was unsuccessful in his first semester in engineering and so had experienced a first-year design course at the university level before he was interviewed for this study. His extra-curriculars during high school included a music program which he described as "quite demanding", and he was the chair of an environmental responsibility team. When asked about any entrepreneurial initiatives, MJ mentioned that he took part in the Shad Valley program in the summer of 2019, and started a small landscape company on his own in the summer of 2020 before coming to Waterloo for the first time.

Shad Valley is a month-long STEAM program for grade 10 and 11 students and is offered in many locations across Canada. Shad Canada describes their program as "university level" with entrepreneurship content and access to mentors (Shad Canada, 2019). The program at Shad includes explicit instruction on design, and includes a significant project where students work in teams to apply what they have learned. The design process that is taught at Shad is described as a "W-model" with 5 phases which are repeated iteratively as students work to solve wicked problems: Define, Ideate, Synthesize, Assess, and Reflect (Moraes, et al., 2019); a process which is described similarly to the better known "double diamond" process model (Design Council, 2019). MJ spoke at length about this process, emphasizing the importance of being creative when imagining solutions before assessing their merits. During the month MJ spent at Shad, he worked in a team of 8 to create a device which could help reduce water waste in Canadian households. The group had access to mentors throughout the process, and MJ described his role as a leader in the team, especially during the design process, but ultimately, he was not that involved in implementing their chosen solution into the physical prototype. When reflecting on the experience, MJ described what he learned about design as: "designing needs to constantly be done over and over again. It needs to be repeated… when you were designing, you need to constantly be going back to the question. It's very important to… [make] sure that it's still doing what you want it to do". The Shad program left a lasting impact on MJ: "coming out of Shad. That was where I decided; that's why I wanted to be an engineer… that design process to me was so much fun."

In his original unsuccessful attempt in first year, MJ took part in a team-based design project in his first-year design course to design a set that would teach science concepts to kids. When asked how the process for this project differed from Shad, MJ commented that there was little room to go back to the problem statement in the design course once solution development started: “The way it was really taught in class… was more like, OK, step one: imagine… 12 ideas and then slowly whittle them down, right? I don’t, I don’t know if there was really that much room to go back to that idea and really grow it again before whittling it down”. MJ perceived that there was not much time for iteration in the process in this design course, but he did comment that the biggest lesson he learned about design was that the transition from design on paper to the physical device is challenging.

Because of the timing of his entry to university, MJ had the majority of his high school experiences in person, prior to the pandemic. He has also had the benefit of an additional year of work experience over most of the other participants while he waited to restart his 1A term, working at both a restaurant, and in hardscaping/landscaping roles. Talking about his landscaping experience, MJ mentioned that he was operating heavy machines and that much of the work was building things like patios and retaining walls. This experience also involved performing some maintenance on these machines, like changing the oil and replacing tracks.

When asked about other design experience he had, MJ mentioned some summer construction projects over the summers of grade 10 and 11; applying physics principles to design and build a zipline in his back yard. He mentioned that YouTube, a mentor, and his father were important sources of knowledge in completing this project, but there was a fair amount of online research that was required as well. In discussing this experience with MJ, the procedural knowledge of design and construction seemed to be his major takeaway: modelling the physics to understand the system was useful early in the process, instead of a trial-and-error approach. When asked how similar the processes from the zipline project, Shad Valley and his university design course were, MJ felt they were “all very different”, and that “the most comprehensive experience was at Shad”. Interestingly, even though MJ had a lot of experience with design and construction over several years of his past schooling, he commented that he doesn’t feel like he fits the mold of a typical engineer; that he never really took things apart growing up, he preferred to build new things instead.

Jay

Jay is a male student who completed his high school in Ontario. Jay’s hobbies included sports, video games, and an interest in science. Jay commented that he wants to become a professional engineer and is enrolled in mechanical engineering at Waterloo to learn the technical skills necessary for that to happen. During high school, Jay had a position working at a charity reseller of household goods/hardware items and enrolled in a computer technology course. This course gave Jay the opportunity to work with circuit boards and electronics and introduced him to CAD software with SketchUp. This course also gave Jay the opportunity to use 3D printers and see simple shapes he created in CAD manufactured in the real world. When asked about the process this 3D printing project used, Jay commented that it was a highly scaffolded set of instructions that the students followed and that this section in the course lasted a couple days. Jay said there was not really an opportunity to be creative in this project, the provided specifications were tightly controlled. Jay did not participate in any other structured design programs, or student clubs, but has experimented with CAD on his own by going through online tutorials. When asked what motivated this work, Jay mentioned that his father (who is a mechanical engineer) pushed him to learn these skills, but that he enjoyed it and continued working on it on his own.

Analysis

The first section of Jay's interview lasted a little more than 9 minutes. He didn't have a lot of prior experience that he thought was relevant, but he has had some formal instruction of relevant technologies in his high school computer technology course. As part of that course, Jay applied a given set of steps to create a simple 3D cubic shape with his name on it, and ultimately 3D printed it. Jay also received some instruction in electronics as part of this course; Jay remarked that they "design[ed] and buil[t] circuit boards… and experimented with SketchUp." Through this experience, Jay could have plausibly developed factual knowledge of common 3D printer materials like PLA, as well as knowledge of electronic components. As they constructed circuit boards in this course, Jay also would have learned some conceptual knowledge of electronics and circuit construction. For procedural knowledge, it is plausible that he was building circuits from circuit diagrams, and he has some familiarity with the steps required to model parts in 3D in CAD, and to manufacture them with 3D printers. Throughout this course, it seems that Jay was provided a detailed set of instructions. For the 3D modelling and 3D printing, this would seem to be more of an "Apply" process, as opposed to a "Create" process. It seems the course had a larger emphasis on the electronics and circuits components, with Jay commenting that they were designing and constructing circuit boards; from this comment, Jay likely constructed circuits using known components, possibly of his own design – implying a "Create" process. It seemed that Jay was frequently working from detailed instructions, inferring more of an application of procedural knowledge relating to circuit construction and verification. Table 56 summarizes Jay's prior knowledge and its development.

Table 56 Knowledge development from background experiences - Jay

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Limited knowledge of 3D printing	High school course project	2. Remember - Recognizing
	Limited knowledge of electronic circuits	High school course	4. Analyze - Differentiating
Conceptual	Knowledge of electronic circuits and their layout and construction	High school course	6. Create – Producing
Procedural	Knowledge of 3D CAD modelling	High school course project; self-learning with videos and projects	3. Apply – Implementing
	Limited knowledge of manufacturing with 3D printers	High school course project	3. Apply - Implementing
	Knowledge of construction and verification of circuits	High school course	3. Apply - Executing

Bond

Bond is a male student who completed his high school in British Columbia. Bond's interest in engineering was sparked by his father who builds airplanes as a hobby. Throughout high school, Bond worked on wood-working projects in his free time, building furniture. He commented that he learned the necessary skills through online videos and watching his dad working on planes. His main extra-curricular activities before Waterloo were primarily sports, with some part-time work refereeing hockey. Bond also had summer employment at a bicycle manufacturing company where he constructed the carbon fibre wheels that were used on the bikes. He was also able to take some of the knowledge he learned about composites to a hobby making fiberglass surf boards for himself and friends.

Bond was motivated to come to Waterloo by his interest in math, and his interest in building things; he saw Engineering as a way to bridge those two interests. While at Waterloo he is hoping to gain the formal education required to be an engineer and to work on problems that are connected to the real world. Like MJ, Bond also took part in the Shad Valley program prior to coming to Waterloo; but unlike MJ, Bond completed the program online during the Covid-19 pandemic and commented that he was not very invested in it. His project used magneto-rheological fluid (a fluid which can alter its viscosity in the presence of electric fields). When asked about the design process, Bond mentioned that the group were taught to go through a design process like that described by MJ, but that his group didn't follow it at all. They decided early on that they wanted to build a damper, and so that's what they did: "[W]e didn't do that at all. We just, oh my gosh, like it has to be a damper… How like a normal damper was used and then just threw extra stuff in it. We didn't really have a goal, we just tried to build something". When prompted, Bond couldn't really remember the design process that Shad had taught him, he just attended the sessions when he was supposed to and did the work that was asked of him. Perhaps due to the online format of the program, Bond's group did not actually construct a prototype, their final deliverable was a report of their ideas and designs. When asked what this process taught him about design, Bond responded that it helped with his research skills and reinforced that you need to investigate what others have done on similar problems.

When prompted further on the impacts of his hobby and employment at the bicycle manufacturing company, Bond commented on the iterative nature of his hobby as he worked on wooden surfboards, then fiberglass, and carbon fibre. He was able to experience firsthand the differences in materials and what they contribute to the final product: "I got to see it work in 100 different ways and I realized, oh, like wood's better for this thing and carbon fibre is better for that thing. And then it's kind of 'Eureka', like oh my god, like it works like that because like the bending, or… like you want it stiff here, you want it flexible there". During this time, he was also receiving some mentorship from an engineer at the bicycle company and learning about the mentor's history in designing bikes. Bond also commented that he enjoyed learning about different topics through online videos. Composite materials (like fiberglass and carbon fibre) and their practical uses seemed to interest him.

Analysis

Bond's most significant experiences prior to starting at university appear to be his work building bicycle parts during high school, and his woodworking hobby. These two experiences provided Bond with a solid foundation manufacturing and assembling wood and composite (i.e. carbon fibre and fibreglass) parts. His progression from wooden to composite surf boards seemed to provide him with a good education on the properties of both materials and how they differ from each other. His experience with wooden furniture making was also quite advanced for someone with no formal training. Bond described the experience of cutting down a tree himself, turning it into lumber, and making a table from it. Bond was self-taught through mentorship from his father and online instructional videos. From this, he would have had to figure out which processes he was capable of doing in his shop and select one; matching the "Differentiating" sub-process in the "Analyze" category, a more challenging cognitive process than many of the other participants who did not extend past the "Executing" sub-process in the "Apply" category. It is somewhat challenging to know what he got out of his experiences helping his father build airplanes, as Bond described his work as mostly passing tools to his father that he had requested; however, he likely learn some knowledge of the various components of small aircraft and how they go together in the bigger systems of the plane.

His final significant experience was his time in Shad Valley in 2020. From his description, this experience is difficult to classify. By his own admission, he didn't take the program very seriously and was not able to describe the design process that was taught to him. Likewise, he commented that they did not apply the design process they were taught in the final project during Shad. This was no doubt a side effect of this experience taking place online in the first year of the Covid-19 pandemic. So, while he struggled to describe the process they were taught, he did complete a design project with some level of supervision from an upper year undergraduate student and received mentorship from one of the bicycle designers where he was employed. From this, Bond should have picked up some basics of design processes, though unlike MJ, Bond did not get to build a prototype of his design during Shad Valley. Table 57 summarizes Bond's relevant prior knowledge.

Table 57 Knowledge development from background experiences - Bond

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Knowledge of materials, design tools, and construction tools relating to woodworking	Self-driven exploration of furniture-making hobby, YouTube instructional videos	6. Create – Producing
	Knowledge of composite materials	Employment at bicycle manufacturer, self-driven hobby building surf boards	6. Create - Producing
	Limited knowledge of airplane components	Helping father build planes	2. Understand - Explaining
Conceptual	Knowledge of construction methods in woodworking	Self-driven exploration of hobby, instructional videos	6. Create - Producing
	Knowledge of bicycle components and systems	Employment at bicycle manufacturer, mentoring by bicycle designer	2. Understand - Explaining
Procedural	Knowledge of manufacturing processes of composite parts	Employment at bicycle manufacturer, self-driven hobby building surf boards	3. Apply - Implementing
	Knowledge of manufacturing processes of wooden furniture	Self-driven hobby, instructional videos, experience building furniture	4. Analyze - Differentiating
	Knowledge of design processes	Shad Valley, mentoring by bicycle designer	1. Remember - recognizing
	Knowledge of entrepreneurship and business practices	Employment at bicycle manufacturer, mentoring by bicycle designer, Shad Valley	3. Apply - Implementing

Oscar

Oscar is a male student who completed his high school at a technical school in Ontario prior to coming to Waterloo. Oscar was always interested in how things work, but once he got to high school and was able to do hands-on building, he really started to focus on engineering. During his high school, Oscar took part in machine shop courses and participated on his school's FIRST Robotics Competition team, in addition to completing a co-op placement during high school. FIRST Robotics is an international robotics competition where teams of high school students design and construct large, remote-control (often with partial automation to supplement remote control) robots to compete in a challenge defined by the event organizers (FIRST, 2024). Oscar likes to take on personal design projects in CAD and described himself as a "very very very amateur woodworker". Oscar's co-op placement in high school was 6 months long at the machine shop in a major local hospital. His project focussed on building lifting devices to assist disabled patients get in and out of machines like an MRI. The designs were created by others, Oscar just focussed on construction and assembly. He also had a paid summer position in 2019 at an automotive manufacturing company with 6 other students from his robotics team. They were hired to design a robot to move materials around the shop floor. In this project, Oscar focussed on the design of the robot, which was sent to an outside vendor for construction. Oscar was drawn to mechanical engineering at Waterloo for the hands-on experiences he felt he could take advantage of (e.g., machine shops, co-op), and while he had a lot of robotics experience, Oscar decided on mechanical over mechatronics because he "hates programming".

Oscar took an extra year of high school as he was debating taking psychology at university and didn't participate in his school robotics that year (2020-2021) but was a part of the team for his other 4 years at the school. Oscar was team captain in 2019 and was a co-lead for the robot design in 2018 and 2019. The robotics team didn't receive much mentorship from teachers at the school, instead relying on older students who had participated in the team in the past. When asked how the team navigated the open-ended nature of the robot design, Oscar reflected on a process of deciding on team strategy first, before deciding on robot mechanisms – a process which he admitted wasn't always followed when he was team captain, but which was very successful in 2020. To help with the design process, Oscar had also curated a set of more than a dozen CAD drawings of other teams' robots from past competitions (many teams openly share their designs with the community) to serve as inspiration. When reflecting on what he learned about design from this experience, Oscar spoke about the importance of iteration – of "fail[ing] fast" – and the ability to reflect on the appropriateness of the design and to be prepared to start over if it was not going to meet the design requirements.

Oscar has extensive experience with using CAD tools. In Oscar's high school tech design class, he was taught CAD skills, but was not taught much about design – the course seemed to follow a linear process from ideation to prototyping to testing. He was, however, able to use the CAD skills to compete in the

Skills Ontario CAD competition (Skills Ontario, 2019), where part of the challenge was adding features to an existing design. The contest documents describe the purpose of this contest as “Evaluating… preparation for employment in the field of Mechanical Engineering using solid modelling CAD software”. In his spare time, Oscar liked to design things in CAD; for the most part, these parts were never manufactured, but he felt going through the process for each of these designs taught him the importance of iterating on a design.

Patrick

Patrick is a male student who completed his high school in Ontario a few years before enrolling at Waterloo; Patrick spent a couple of years playing competitive hockey before enrolling in mechanical engineering at Waterloo. Patrick originally thought about applying to software engineering, but through his hobbies he realized he really enjoyed the more tangible nature of mechanical engineering. When asked about any experiences at high school which relate to design or engineering, Patrick really didn’t have much to say; hockey took up most of his time outside of school. Aside from hockey, Patrick had been a hobbyist woodworker for several years and had spent a year working at a custom furniture maker during the pandemic. Patrick also had some experience with 3D printing, he designed several parts for his workshop in CAD and 3D printed them. When asked if he had anyone mentoring him in his hobby, Patrick responded that he was self taught using YouTube videos.

Jill

Jill is a female student who completed two years of high school in the United States before finishing high school in Ontario. Jill has been interested in science since she was a kid, and it was her experience in the Science Olympiad in grade 10 that really convinced her to pursue mechanical engineering. Jill is interested in aerospace and biomedical applications and saw mechanical engineering as one discipline that could enable her to move in either direction later on in her career. At university, she is looking forward to learning more about mechanical engineering design. When asked about the difference between her two high schools, Jill commented that all of her prior STEM experience took place at the American school; she didn’t perceive the school in Ontario providing her any accessible STEM-related experiences.

Jill’s Science Olympiad competitions at the American high school included a design-build of a Rube Goldberg machine, a design-build of a small plane from a common set of parts, as well as other events. For the design-build activities, there was no set process that she used, instead “it was mostly like trial and error, like I would build something and then I would test it out, either at like my school, or directly at a competition… we had several competitions throughout the year." She commented that she didn't have access to any mentors during the building, but she did receive feedback from professors and/or teachers at the competitions. Throughout these competitions (which took place over a couple of months), Jill was refining the same prototype. Jill commented these design-build activities were tightly controlled with detailed instructions, and restrictions on what could be created.

Jill had also taken part in a hackathon in the month before enrolling at Waterloo. She had taken AP computer science in high school, and she treated the hackathon as a litmus test of whether she enjoyed programming enough to pursue it in the future. During the hackathon, Jill focussed on the user interface design of the app they were creating, while other team members worked on the coding aspects of the project. When asked what these different design experiences had taught her about design, Jill commented "I just feel like you have to test your designs a lot. Like the only way to improve, like for me… is to test it." When asked how she would navigate a design situation where the prototype was too big or expensive to build and test its functionality, Jill was not able to communicate any tools or processes which could help her navigate the situation. Jill also commented that her experience with programming helped her learn how to be a better problem-solver and helped her with testing her design solutions. It appears that Jill is most comfortable iterating on a design through testing and validation of prototypes.

Analysis

Jill has good experience with beginner/intermediate programming concepts through her AP course in computer science. According to the course curriculum, AP Computer Science A is "an introductory college-level computer science course", where students learn about topics like primitive types, object-oriented programming, expressions, iteration, containers like arrays, inheritance, and recursion in Java (College Board, 2020). This experience combined with the hackathon just prior to coming to Waterloo would have provided Jill with good experience writing her own programs, testing, debugging, and iterating. It is somewhat difficult to assess the level of procedural knowledge Jill would have attained during these experiences, however, a typical first-year university programming course does not have the time to present more than a single software development process. Similarly, these courses frequently do not cover common procedures in software engineering like searching and sorting (which typically are taught in a second course), though the AP computer science curriculum does mention simple algorithms like finding a maximum or average value of a set of numbers. At a minimum then, Jill could be expected to implement processes she was taught in new problems (i.e. "Apply" in the cognitive process dimension), but it is unlikely that she was analyzing, evaluating, or creating new processes.

Through Jill's experience in Science Olympiad building a plane out of provided materials, she researched concepts relating to the aerodynamics of airplanes, selected the form for her plane, and built and tested it. Over the course of several weeks, and through the testing of her prototype on her own, and at competitions, she was able to optimize its shape for the constraints of the competition. She described adjusting the plane's shape, launch mechanism, and centre of gravity to optimize its flight time and got exposure to materials like wood and carbon fibre during this process. From Jill's comments, the process of building and refining the plane was largely self-driven, with sporadic feedback from mentors, and extensive instructions from the competition organizers. Jill certainly would have developed knowledge of planes through this experience, however given her age at the time of this experience (grade 9/10), it is difficult to understand the depth of her level of understanding without further probing. Jill's experience with the plane challenge, and the Rube Goldberg challenge in Science Olympiad also would have given her some experience with common construction materials and processes (e.g. cutting various materials like cardboard and wood, joining common materials with adhesives and fasteners, etc.) as both competitions required physical prototypes.

Table 58 Knowledge development from background experiences - Jill

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Knowledge of beginner/intermediate software engineering concepts	AP computer science course in high school	6. Create - producing
	Limited knowledge of airplane concepts, materials, and individual components	Science Olympiad competition in grades 9/10	5. Evaluate – critiquing
	Knowledge of common crafting materials and tools	Science Olympiad competition	3. Apply - Implementing
Conceptual	Knowledge of beginner/intermediate software engineering principles	AP computer science course in high school, hackathon	6. Create - producing
	Limited knowledge of airplane assemblies	Science Olympiad competition	6. Create – producing
	Knowledge of common construction methods	Science Olympiad competition	5. Evaluate – critiquing
Procedural	Knowledge of beginner/intermediate software engineering processes	AP computer science course in high school	3. Apply - Implementing

When asked what these different design experiences had taught her about design, Jill commented "I just feel like you have to test your designs a lot. Like the only way to improve, like for me… is to test it." When asked how she would navigate a design situation where the prototype was too big or expensive to build and test its functionality, Jill was not able to communicate any tools or processes which could help her navigate the situation. It appears that Jill is most comfortable iterating on a design through testing and validation of prototypes. Jill is similar to Oscar in many ways: she has experience with iteration and construction and little formal design training; though she has less overall depth of experience than Oscar. Table 58 gives an overview of Jill's knowledge with the expected cognitive processes employed.

Michelle

Michelle is a female student who completed her high school in Ontario prior to coming to Waterloo. Michelle's extra-curriculars and hobbies in high school tended to be athletics-related, though she credits her interest in Formula 1 racing as the reason she chose to pursue mechanical engineering. When asked to expand more on this, Michelle commented that she read an autobiography by a Formula 1 designer that she found interesting. She also commented that she is interested in being more hands-on in her work, as opposed to fields that are more software oriented. Michelle has participated in hackathons before coming to Waterloo, as well as a program called Technovation (Technovation Girls, 2023). Technovation connects high school girls with mentors from the business community to create apps which solve local problems in the community. Michelle's project was completed in a group of 5. Michelle commented that there was both a prototype and a business component in Technovation, but her focus was on the app prototype development. Technovation ran in-person, over the course of approximately 3 months during the school year (but wasn't affiliated with her high school), and had weekly meetings where mentors instructed on topics like prototyping, user friendliness in design, collecting feedback, and other business topics; ending in a pitch competition. The app prototype was not built from scratch, the students were instructed to use a website which helped construct the app from pre-engineered building blocks. Michelle described the process used by Technovation as "semi-structured", and which sounded like an agile software development process from her description (though she did not mention these words directly). When reflecting on what this program taught her about design, Michelle mentioned teamwork in designing, and the challenges of implementing someone else's design in reality. From her description, functional testing was an important part of the process throughout as they refined their app design.

Michelle also participated in several online hackathons during high school, typically working in groups of 3 or 4. These hackathons were 1-2 days long and followed a similar process each time: they drew out a basic template of the website, implemented the user interface in Figma, and then built the site with CSS/HTML. Michelle has also completed some independent software projects, but nothing in the mechanical realm. When asked what her software experience taught her about mechanical design, Michelle felt the process was similar: identify a problem, develop a prototype, collect user feedback, and improve on the solution.

Michelle was the last interviewee for this study and was not interviewed until just before Thanksgiving. As such, she had more of an opportunity to participate in extra-curriculars at Waterloo than the other participants. When asked, Michelle mentioned that she had joined the Formula student team (where they construct a small single seat race car for a competition each year), and that she had completed the machine shop orientation training as part of her work with the team. As this interview happened later in the term, Michelle also had an extra week or two of instruction in her first semester design course before the interview. At this point in the term, the main lessons that stood out to her were the technical drawing skills (both hand sketching and AutoCAD), and some design philosophy/process knowledge: don't jump to a solution too quickly, as well as some tools to help evaluate different solutions and select one to pursue.

Appendix D Detailed Data – 1A Design Activity

MJ

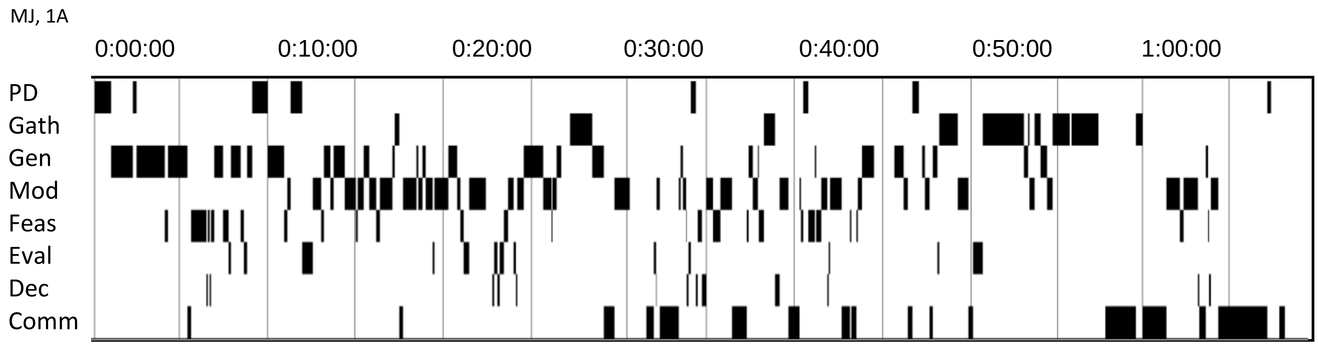


Figure 41 Design timeline of 1A interview with MJ

After writing down the design prompt, MJ jumped immediately into a brainstorming process to come up with as many different ways to open a jar as possible (section a in Figure 11). These included solutions that were both practical (e.g., a machine which automatically opens the jar) and impractical (e.g., a bomb that would destroy the jar but release its contents). Throughout this process, he focussed on divergent thinking to generate options, and withheld any judgement; he described this as a "yes, and…" approach. After 5 minutes of generating ideas, MJ transitioned to looking at them critically to figure out which approaches might work (section b in Figure 11). In this initial evaluation, MJ focussed on evaluating the feasibility of each of the ideas by thinking through how each concept would operate. As he went through his concepts again, he started categorizing the ideas (e.g., solutions that focus on the lid, vibrating devices, etc.). The criteria he thought about during this process were cost, potential for damaging the jar, and the presence/absence of motorized elements.

At the 9-minute mark, MJ began thinking more about what it means that the user has disabilities (section c in Figure 11). This led to another round of brainstorming as he thought of a new category of solutions: the user relying on other parts of their body to use/interact with the device (e.g., using your foot). MJ then thought of a new requirement for his device: perhaps it should help the user close the jar as well. With a few categories of solutions available to him, MJ began working on the details of some that he judged to be more feasible (section d in Figure 11). During this time, MJ spent a minute or so on each method for opening a jar, thinking about how that method could be translated to an actual device. Around the 18-minute mark, as he was thinking about part of a design which held on to the jar, MJ searched around his room to find a similar mechanism, which he found on the buckles which held a small briefcase closed.

At 23 minutes, MJ transitioned back to an evaluative mode, trying to find the “best” ideas (section e in Figure 11). He also commented that combining some of the traits of different solutions may be possible. As he switched from divergent thinking to convergent thinking, MJ commented: “So now some of what I'm starting to think is I'm going less from Shad, which is design kind of ideation… And now I'm gonna move more on to what I've learned last year and a little bit this year now from Professor, which is the actual designing. Going to create a draft design.” As MJ began to narrow down his concepts, he eliminated any solutions which damaged the jar lid. He also tried to stay away from motorized devices, which he felt would end up being too expensive. As he continued to think about his device, he struggled to solve a sub-problem for his design: how to attach the device to the kitchen counter. While thinking about this, he also realized an additional requirement: the device should be adjustable for different jars. This line of thinking generated an idea for a new family of solutions, and so MJ transitioned back to thinking through some of the design details for these new options (section f in Figure 11). His online search at 27 minutes was to find the torque required to open a jar. During this search, MJ found a research paper that sought to answer this question, but he did not read it in any detail before shifting to sketching some of the concepts he was still thinking about. At the 30-minute mark, when MJ was asked to share what he was sketching, he spent a minute or so adjusting his camera for the recording to better show what he was doing. As he talked through his designs, he refined some small details on the concepts, before coming to one concept where he commented: “Uh, and this next one, which is personally my favorite idea and the one I'm leaning more towards at the moment.” When he got to the last concept he was still thinking about (the foot-powered device), he couldn’t think of an easy way to transfer the force from the user’s foot to the device, and quickly ruled that out as a possible solution (section g in Figure 11). Once that solution was off the table, he selected his main device concept, focussing on “simplicity”.

With the general design concept chosen, MJ was not sure how to proceed, commenting: “So here's where... this is where I become… more directionless… so this is where I'm now going to need to probably consult some of the Internet to actually create a comprehensive design. Right, because the design uhh the design I have now is. Umm… It's not going to be… not going to be the uh… the most... you know, like I don't know how… well it's actually gonna work… its function is gonna work. So. I'm gonna do my best to… to draw something out. My best estimation, of what it will be, and then I'm going to have to consult some sources online." MJ started the detailed design of his device by focussing on the part that would clamp on to the lid (section h in Figure 11). As he sketched what the device would look like, he also began writing the user instructions for how the device operates. As he talked things through, he realized it would be challenging to install the jar in the device with only one hand. He was uncertain how to address this issue in his design and so went to the internet to search common jars. After a quick search, MJ had an idea to resolve his design issue and continued working on the solution. His new idea was to fasten the device onto the bottom of the kitchen cabinets so it could firmly clamp the lid. Around the 41-minute mark, after pursuing this idea for a few minutes and thinking about the difficulties of installing the device and using it, he switched the design to something that attaches to the counter and holds the jar.

MJ's second iteration of the design was a sort of adjustable clamp that is "stuck" to the counter that holds the jar (section i in Figure 11). Once he had most of the concept sketched out, MJ clarified how far he needed to take the solution. During this back and forth, he commented: "my knowledge kind of ends on, you know, knowing how much of a certain material I'm going to need, or how like what will actually be enough to stop it from, you know, from… I I'm not. I'm not exactly sure, you know, say what the torque is, or what's needed to make sure it works. But I know enough to give a like a… I'll give like I guess I'm maybe uh… do my best… I don't know, it's not exactly proof of concept but I'll do my best to show the mechanics of what, how it would work." From 45 minutes to approximately 47 minutes, MJ worked on two alternatives for the portion of his device that would clamp around the jar. Before he could evaluate and decide on which method he wanted to go with, he went to the internet to search for "tightening mechanisms". He appeared to struggle with the search, commenting: "Unfortunately, my knowledge on any of this stuff kind of prevents me from… uh… really understanding any of this." While the search online didn't lead directly to any new concepts, MJ had the idea of using a mechanical iris as an adjustable way to hold on to the jar. He liked this mechanism for his device, but could not provide strong reasoning for his choice, instead commenting: "This one makes the most sense to me. I can… you know I've seen stuff like this before. and I've seen umm… how simple it is to use."

Beginning at the 51-minute mark, MJ went back to the internet to find out more about his chosen mechanism (section j in Figure 11). He was not able to name the concept he had selected as an "iris" and so continued to search "tightening mechanisms". During these few minutes, MJ went from website to website quickly; occasionally commenting on things he saw that were interesting, though ultimately did not incorporate any of things he saw into his design (though they did occasionally spur other thoughts, like gears could be used in his solution). As these ideas came to him, he added or refined details on his design before continuing his search. At the 57-minute mark, MJ stopped his online search and began working on a final sketch of his chosen design (section k in Figure 11). During this final window of time, MJ occasionally had to resolve issues or deficiencies in his design. He also looked online for the diameter of standard jars and then did a quick calculation to determine the important dimensions for his device. With these last details decided on, MJ wrote a final set of instructions for the operation of his device. MJ completed one last check of the problem statement just before concluding his design.

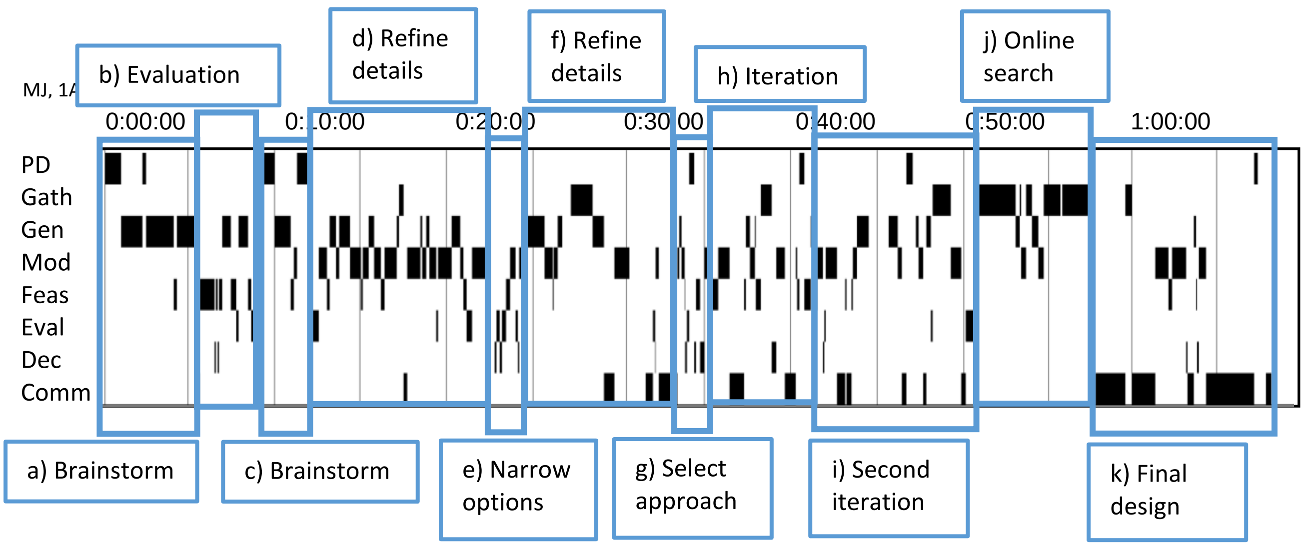


Figure 42 Overview of design process, 1A interview with MJ

Jay

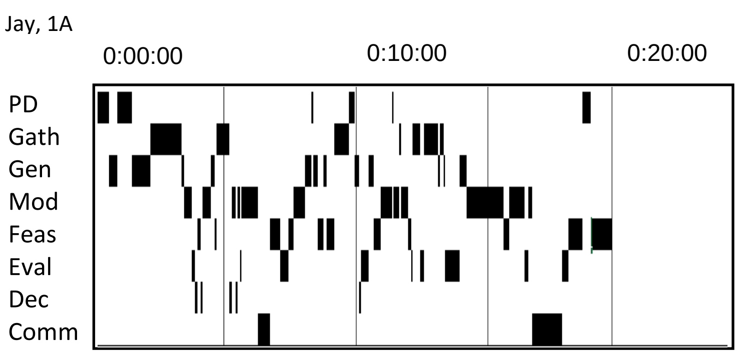


Figure 43 Design timeline of 1A interview with Jay

Jay started by thinking about his own struggles with opening jars, and identified three main features his solution would need: grip on the lid, leverage to help open it, and something to hold the jar (section a in Figure 44). Jay also thought about some other requirements, like the device should be portable. After starting to sketch a jar, Jay realized quickly that he didn't have a good idea for how to hold a circular object stationary and went to the internet in search of ideas for a clamp (section b in Figure 44). He ultimately found and settled on adapting an oil filter strap wrench for holding the lid of the jar. After commenting that the same device could work for holding the jar as well, he became concerned about the robustness of this solution, and quickly tried to find another solution online for the part of his device that would hold the jar, but struggled with identifying a search term that would lead to useful design suggestions. Ultimately, he went back to the oil filter strap wrench for holding the jar and the lid.

As Jay worked on integrating the existing strap wrench device into his solution, he transitioned rapidly between virtually all steps in the design cycle (section c in Figure 44). After sketching a jar with a strap wrench on both the lid and the jar, Jay realized he might need some structure to connect the two parts into one unit. As he thought about this, he recognized that it may be difficult to accommodate jars of different sizes in his device if the two mechanisms are rigidly connected. This led to the identification of some shortcomings of the design, and some adjustments to the requirements of the device, before he went back to his online search for other ideas. Around the 10-and-a-half-minute mark, Jay ultimately decided to leave the device that clamps the jar and the lid as two separate devices, and that the portion which holds the jar should be clamped firmly to the kitchen counter (section d in Figure 44). At this point, Jay began to think about how the device would be held to a table or countertop.

After finding one solution for clamping the device to the counter (a common c-clamp), Jay began thinking about integrating the jar clamp with the clamp for the counter. At this point, Jay restarted his original search for a clamping mechanism for the jar (section e in Figure 44). During this second search, he evaluated a couple of other options, but kept returning to the original device he found. Once this second search turned up no other useful mechanisms, Jay turned to sketching a more detailed concept of his solution (section f in Figure 44). His focus during this time was on modifications to better hold the jar, as well as the integration of the clamp that holds the jar with the clamp that holds it to the counter.

Around the 17-minute mark, after he had been sketching for a few minutes, he was requested to show the solution in progress. After walking through his design, he completed the design activity by critiquing the shortcomings of his design, which included aesthetic challenges, and issues with a user with limited motion in their hand using his device but did not attempt to improve his design at all (section g in Figure 44). As he walked through his design, he conducted a sort of intuitive evaluation, but did not employ any robust criteria. At one point as he was reflecting on the clamp that holds the jar, Jay said: "Uh, so it could be secured to a table for like a semi permanent solution and the… the top portion that actually grips onto the jar would stay unchanged because I actually think it's a decent design as of now so it doesn't really need to be modified in any way." Ultimately the solution was able to perform the three functions he originally identified but was not developed beyond a simple concept and may be challenging for users with different physical disabilities to operate.

Jay completed the live design activity in 20 minutes, the shortest time of any of the students (see Figure 44). During his design process, he transitioned between steps 64 times (which was the highest rate of any participant at 3.2 transitions per minute).

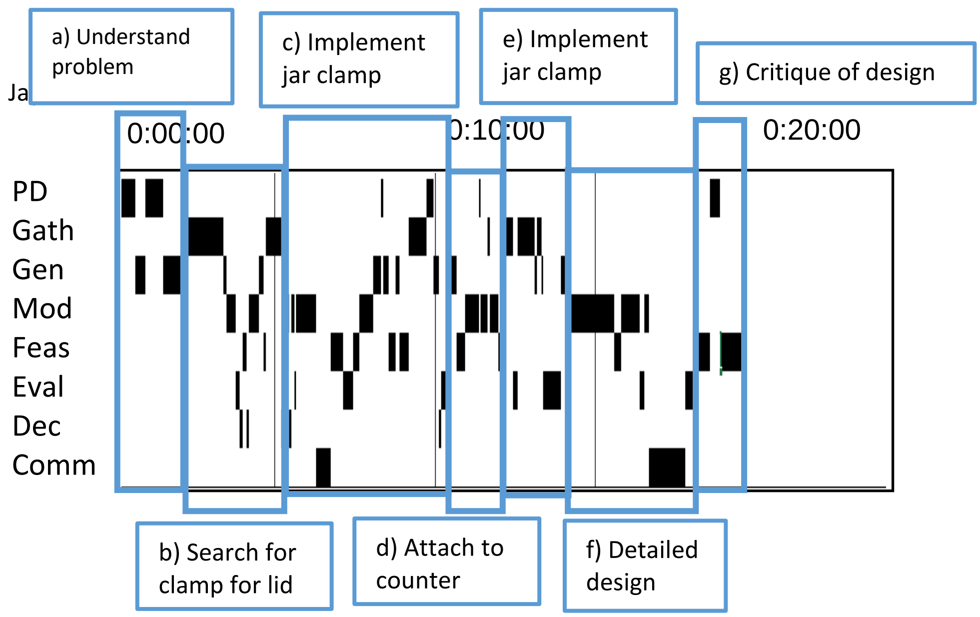


Figure 44 Overview of design process, 1A interview with Jay

Analysis

Reflecting on the behaviours of a beginning designer described by Crismond and Adams, Jay:

- spent some time understanding the requirements for the device, but did little to no iteration on the problem definition as the solution proceeded,
- struggled to conduct a broad search for design ideas,
- fixated on the first useful mechanism he found in his search,
- conducted limited tests of his proposed design,
- designed a device that would be challenging to both install and operate with a single hand,
- made decisions without weighing any options, and
- included no iteration and only limited reflection during the process

Table 59 shows the percentage of his total design time that Jay spent in each design step. While Jay spent more time in modelling than in any other single step of the process, he spent a fairly balanced percentage of his time in each step (except for decisions where he spent virtually no time).

Reflecting on the behaviours of a beginning designer described by Crismond and Adams, Jay:

- spent some time understanding the requirements for the device, but did little to no iteration on the problem definition as the solution proceeded,
- struggled to conduct a broad search for design ideas,
- fixated on the first useful mechanism he found in his search,
- conducted limited tests of his proposed design,
- designed a device that would be challenging to both install and operate with a single hand,
- made decisions without weighing any options, and
- included no iteration and only limited reflection during the process

Table 59 Percent of time spent in each design step during 1A interviews, Jay highlighted

Design Phase	Chris	MJ	**Jay**	Bond	Oscar	Patrick	Jill	Michelle
Problem Definition	10%	6%	**9%**	12%	8%	4%	15%	1%
Gather Information	1%	13%	**17%**	8%	4%	33%	12%	14%
Generate Ideas	8%	20%	**12%**	13%	26%	22%	14%	17%
Model	37%	23%	**26%**	19%	29%	2%	38%	38%
Feasibility Analysis	10%	7%	**16%**	6%	4%	5%	3%	3%
Evaluation	1%	4%	**10%**	2%	10%	15%	5%	5%
Decision	1%	2%	**2%**	1%	0.4%	3%	1%	4%
Communication	23%	18%	**8%**	23%	14%	3%	10%	10%
Transitions (mean=83)	50	148	**64**	112	75	112	40	62

As with Chris, Jay demonstrated many of the behaviours of a beginning designer, ultimately finishing the design activity having only thought about a single design concept. Unlike Chris, however, Jay attempted an online search of other mechanisms that could help him complete his design, but he struggled to conduct a useful search, trying a very limited number of search terms to find something useful. Once he found one mechanism that was workable, Jay used that device in his design for both holding the jar, and for grabbing on to the lid, even though he identified issues with its use in this design problem near the middle of this design activity, and again at the end. It was interesting that Jay's prior experience with solid modelling (which Chris didn't have) didn't appear to help him produce a solution which could be manufactured. It is possible that his time learning CAD was focussed on the mechanics of using CAD tools, and not on the process of designing devices using the software. Jay's knowledge of electronics was ultimately not useful in this particular design as he created a mechanical device.

Table 60 A summary of Jay's prior knowledge, adapted from Table 17

Prior knowledge	Factual		Conceptual		Procedural	
Relevant factual/conceptual; limited procedural knowledge	3D printing Electronics	Low Medium	Electronics	Medium	3D modelling 3D printing Electronics	Low Low Medium

Bond

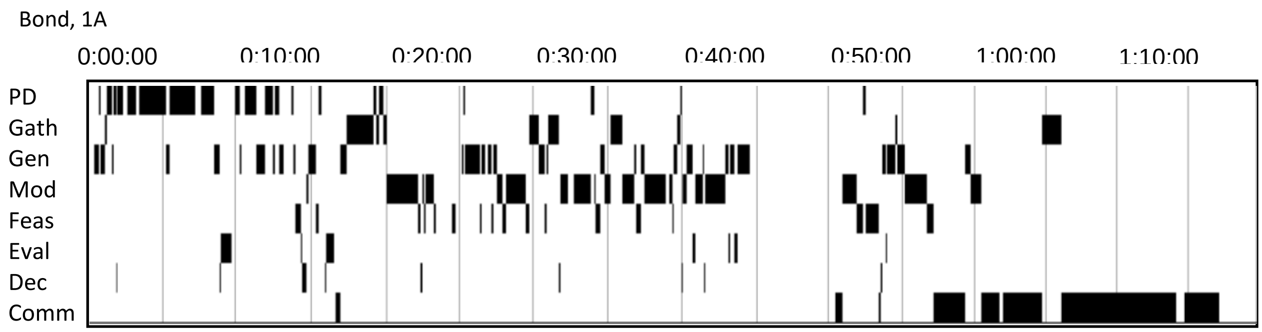


Figure 45 Design timeline of 1A interview with Bond

Bond began by reminding himself about the engineering design process, and the value in lateral thinking early in the process to come up with as many ideas for a solution as possible (section a in Figure 46). To come up with ideas, Bond thought about the function the device would need: something to spin the jar lid and jar in opposite directions. He made an early decision to build a stationary device that would sit on the counter. At approximately 2.5 minutes into the session, Bond began talking about the lessons he had been taught in ME 100, specifically during the "coffee maker dissection" activity. From that, he began thinking about the function that his device would need: a closed jar would go into this device, and an open jar would come out the other side. From here, he began writing out the criteria and constraints: a step that was taught to him in ME 100. As he ran through the constraints and criteria for the device, he thought about its cost, its physical size, that he would like to keep it mechanical in nature, with no need for electricity. He also thought about different aspects of safety as they relate to the device. After the first 8 minutes, Bond began thinking about the way he would like the machine to operate and acted out its operation with the water bottle he had on his table (section b in Figure 46). He came up with two general directions for his solution to take: a user holds the jar up to a machine and the machine grabs the lid and twists it off, or the user installs the jar in the machine and then uses their hand to power the lid off. He talked through the general safety and repeatability of the two approaches and decided the second approach would be the one to pursue. After briefly considering the impact of this approach on his existing constraints, Bond moved on.

At the 10-minute mark (section c in Figure 46), Bond began thinking about what his solution would look like, before stopping and reminding himself that ME 100 taught him to think about the problem before coming up with solutions: “Right now I'm thinking what it would look like, maybe like a… which I shouldn't think of. Ah… Prof would have me… I'm thinking maybe like a coffee machine or something, but I shouldn’t think of what it what it looks like right now.” After deciding he shouldn’t think about solutions yet, Bond went back to thinking about the functions and constraints and criteria for his device. He also began thinking about mechanisms that he was likely to require in his solution, like gears as a way to transfer forces and their direction within the device. At this stage, he began thinking about what his constraints meant for the solution. His general approach for the device was to have a large lever that the user would pull down on to open the jar. At this point, he began focussing on how to translate that force to something that could spin the lid off the jar. Ultimately, he decided that a cable which slides through an outer sheath (like the brake cable on a bicycle) would be a good way to transfer the user’s energy to the jar lid.

Around the 17-minute mark (section d in Figure 46), Bond went to the internet to gather more information on jars (for example, their diameter, the number of turns to remove the lid, etc.). This information ultimately informed the requirements for his device. Once he had the information he needed on mason jars, he began designing the mechanism for removing the jar lid in more detail (section e in Figure 46). After 25 minutes, Bond shifted his focus to how to grab on to the lid. For this component of the design, he came up with a single solution that featured 3 fingers which will close on to the lid as the user pulls down on the device’s lever. This mechanism was integrated with the cable mechanism that will spin the lid off, Bond wanted to integrate these movements together so the device would be easy for the user to operate. At the 30-minute mark, Bond went back to the internet to investigate the surface texture of jars and their lids to help in his decision on the design and material for the “fingers” which would grab on to the lid. At the 32-minute mark, Bond struggled to analyse his device to determine how much clamping force would be required: “I'm just trying to think if there's an equation for how much clamping force you actually need… compared to rotational force, so just for just for friction. I’m sure there is, but I don't think I need to do too much analysis right now. Or I’m, I'm just not able to. That's my best excuse for not doing that. um… I'm not smart enough for that stuff. That's what I'm here for.”

With the design of the lid removal portion complete, Bond started thinking about the part of the device that would hold the jar (section f in Figure 46). Beginning around the 34-minute mark, Bond began thinking about the requirements for this part of the device, quickly brainstormed some ideas, and then went back online to research the height of standard jars. After about 2 minutes of thinking about the part that holds the jar, Bond moved to thinking about the structure of the device that would connect the lever, the lid removal component, and the jar holding component. As he designed the jar holding component and the overall structure of the device, he revisited his constraints and criteria to remind himself of what the solution required. He also conducted a very brief search for "soft surfaces" when looking for inspiration for materials which can cushion the jar. The time from 40 minutes to the break at 45 minutes was largely focussed on the details of the base design that would hold the jar in place. As he thought about the various issues in his design, he reiterated that he was actively avoiding any electronic components like sensors, and so had to find other ways to solve these issues. At the 45-minute mark, Bond took a short break away from the recording (section g in Figure 46).

Upon his return, he had clearly been thinking about the base design while he was away. He came back and immediately started sketching a clamp design to hold the jar (section h in Figure 46). When thinking about his design, Bond was most concerned with the user experience of the device, he wanted to make sure that the jar always stayed vertical when placing the jar in, or removing the jar out, of the device. Staying with his requirement to avoid electronics, instead of motors Bond incorporated springs in the bottom of the device to apply the upwards force needed to engage the jar with the mechanism that will remove the lid. In addition to the spring in the base, Bond wanted to include a scissor lift mechanism under the jar. It seemed like he wanted to search online to see how these mechanisms worked, but he couldn't think of the name of the mechanism and so he didn't actually gather any information on the mechanism beyond what he already understood. Once he had sketched a design for the lifting platform, he spent some time on the supports that will hold the jar in place in the device.

Beginning at the 57-minute mark, with the overall concept of the device sketched out, Bond shifted to a more detailed design and description of the device starting with the portion that removes the jar lid (section i in Figure 46). As he worked on the final version of the design, at the 1-hour mark, he ran into one last detail to figure out: how to attach and route the cable through the device so it could perform the job of removing the jar lid. Bond's final search online at 1 hour and 5 minutes, was to see the inner workings of a drill chuck as he was using a similar mechanism in the lid removal portion of his device. After incorporating those details in his design, he transitioned back to the base of the mechanism and then to how the whole system will come together (section j in Figure 46). In the last 2 minutes of the design session, Bond presented his design and its operation to the interviewer (section k in Figure 46).

Analysis

Bond completed the live design activity in 77 minutes, 10 seconds, the longest time of any participant even after factoring in the 5-minute break at the 45-minute mark of the activity (see Figure 46). Over that time, Bond transitioned between design steps 112 times, at an average rate of 1.45 transitions per minute: a below average rate.

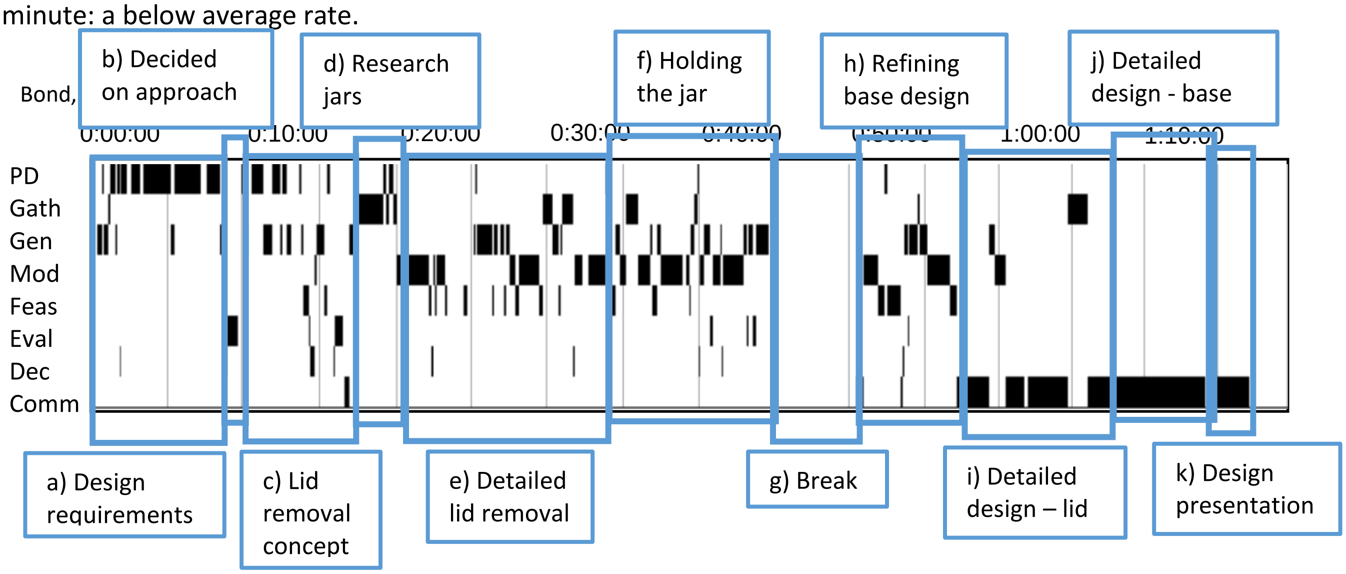


Figure 46 Overview of design process, 1A interview with Bond

Table 61 shows a summary of the percentage of total design time that Bond spent in each step of the design process. He did not spend very much time in evaluation or decision-making but otherwise was balanced between the different steps. Overlaying the cascade shape that Atman proposes shows that Bond's process overall appears more expert-like than most of the other participants.

Table 61 Percent of time spent in each design step during 1A interviews, Bond highlighted

Design Phase	Chris	MJ	Jay	**Bond**	Oscar	Patrick	Jill	Michelle
Problem Definition	10%	6%	9%	**12%**	8%	4%	15%	1%
Gather Information	1%	13%	17%	**8%**	4%	33%	12%	14%
Generate Ideas	8%	20%	12%	**13%**	26%	22%	14%	17%
Model	37%	23%	26%	**19%**	29%	2%	38%	38%
Feasibility Analysis	10%	7%	16%	**6%**	4%	5%	3%	3%
Evaluation	1%	4%	10%	**2%**	10%	15%	5%	5%
Decision	1%	2%	2%	**1%**	0.4%	3%	1%	4%
Communication	23%	18%	8%	**23%**	14%	3%	10%	10%
Transitions (mean=83)	50	148	64	**112**	75	112	40	62

Evaluating Bond's design process using Crismond and Adams, Bond had a mix of beginner strategies, and those of someone with more experience:

- Bond delayed starting on a solution until he had though about the problem and formulated some criteria and constraints for his device
- Bond did some research, and also gathered information through his interactions with the water bottle he had with him, though his searches were conducted very quickly and he often struggled to find the information he needed
- Bond did generate some alternatives for his solution, but typically only 1 or 2 before making a decision and moving on
- Bond sketched some details of the inner workings of his device, but they were missing detail (e.g., dimensions, material choices, fastening details, etc.). It is also unclear if the device would ultimately work, as it was quite complex, especially in how it removed the lid.
- Bond did not spend much time or effort evaluating his options and making decisions; he recognized at times that he did not have the knowledge to complete the analysis that he would like to do, but even with this missing knowledge, most of the decisions were made intuitively. At most, Bond would consider the general feasibility of the option, or whether it achieved the device's requirements when selecting it, but there was little depth to this process
- Bond attempted to manage his design process, especially early on; consciously slowing himself down in making decisions. Bond also went over the entire design of the device as the individual components were integrated

Bond was clearly influenced by ME 100's teaching, especially in the early stages of the design session. By the time he was interviewed, he had gone through at least one hands-on design activity in the course: the coffee maker dissection, which really shaped how he thought about the problem early on. Bond also explicitly considered the criteria and constraints for his device: a method taught in ME 100. Bond seemed to explicitly alter his design process to better match what he was taught in ME 100; appearing to struggle a bit at times as his natural instincts for how to solve the problem clashed with what he had been taught. While it is hard to say whether it was the influence of ME 100, or the natural way he thought about the device, but Bond proceeded through the design by decomposing the various functions for his device: the mechanism that would remove the lid, the mechanism that would lift the jar to engage the lid mechanism, and the details for holding the jar steady.

Table 62 A summary of Bond's prior knowledge, adapted from Table 17

Prior knowledge	Factual		Conceptual		Procedural	
Relevant factual/conceptual; limited procedural knowledge	Woodworking Composites Airplanes	Medium Medium Low	Woodworking Bicycles	Medium Medium	Composites Woodworking Design	Medium Medium Low

In addition to the knowledge used from ME 100, Bond drew on his experience with bicycles as the mechanism to transfer the user's energy to the jar lid; he picked up on the fact that he was drawing directly on an experience we had just talked about: "I guess it's a little bit of a past experiences with the bike." His knowledge of other useful mechanical engineering constructs was quite limited, however. He frequently struggled with coming up with the names for mechanisms he wanted to use, making online searches challenging. As with many of the other participants, when Bond was conducted the detailed design of his device, he would frequently struggle to vocalize his thoughts, and even once he began talking, he would sometimes struggle to put his thoughts into words. Bond also struggled at times with conducting a proper analysis to aid in his design decisions (like at the 32-minute mark when thinking about clamping force).

Bond was one of the few participants to spend significant time in the communication step. Most of the sessions concluded with some time spent in communication at the request of the interviewer, but Bond naturally transitioned to this step and spent a significant amount of time there, polishing details of the design and communicating its function. Ultimately the design was still missing significant technical details that would make it challenging to manufacture, but Bond did invest time in sketching both the overall concept, and sketches of mechanisms in his device to communicate how they operated.

Oscar

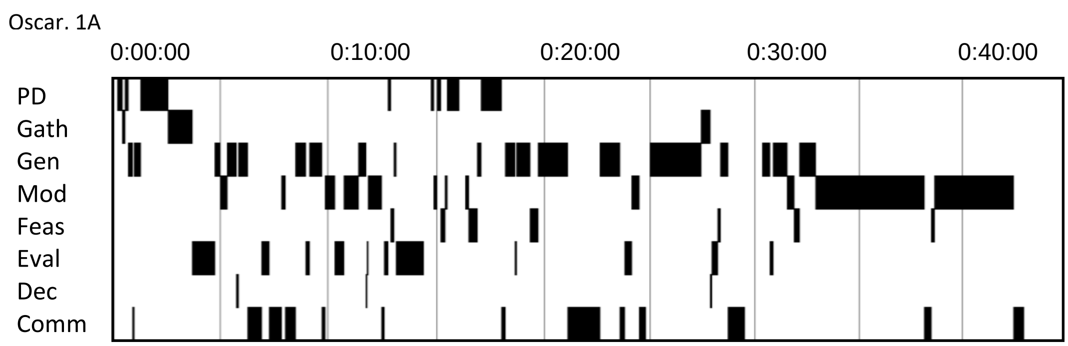


Figure 47 Design timeline of 1A interview with Oscar

Oscar spent his first few minutes attempting to better understand the problem, as well as some overall design directions like whether to include electronics in his solution or keep it mechanical in nature (section a in Figure 12). During this time, he conducted a short thought experiment about how a hand functions as it opens a jar and spent some time writing requirements for his solution. When writing his requirements, he used the language of what the design "needs to have" and what it would be "nice to have", which are commonly referred to as "constraints" and "criteria", respectively, in ME 100, but never actually used the words constraint or criteria. It is still possible, however, that some of the instruction from ME 100 is coming through in his process (Oscar's interview took place after about 2.5 weeks of his 1A term). After 2.5 minutes, Oscar also began thinking about existing devices that are used to open jars that he was already familiar with, before going to the internet to look at what solutions already exist (section b in Figure 12). Unlike most of the other participants, Oscar didn't go out looking for general assistance online, he searched specifically for "jar opening tool one handed", finding several options that did not come up for the other participants. During this search, he was thinking about what parts of the existing solutions he liked, and didn't like, before transitioning to some sketching. As he transitioned to sketching, he commented: "I'm going to start sketching, because I don't know what else to do".

Over the next minute or two, Oscar went silent and began sketching (section c in Figure 12). When asked to continue verbalising his thoughts, he showed an initial design concept to the camera. This concept consisted of a base that suctioned to the counter, and which held the jar stable so you could take off the lid with one hand. He did not seem to spend much time on decision-making, moving forward quickly with his concept; clearly, he made decisions along the way, but did not vocalize these thoughts. Evaluation also did not seem to take place until after he communicated the concept to the interviewer, then he transitioned to justifying some of the choices he made. This initial concept was similar to some of the solutions he saw online, but also included a mechanism that he thought of at the start of this segment of the design activity: left-handed threads that self tighten as you open the jar. After presenting the first design, Oscar deliberately went back to see what other solutions he could come up with.

Oscar's second concept was based off a specific device he had at home (section d in Figure 12). While starting to sketch this solution, he realized that his first solution lacked adjustability for different sized jars. Thinking about this solution also led to some ideation and evaluation of suitable materials for his solution. As with his first design concept, as he was sketching the details of his design concept, Oscar struggled to sketch and talk at the same time. Instead, he would go quiet until either being prompted to continue speaking his thoughts, or he finished what he was working on, and then he would present his solution. His second concept included a device that could slide on to the lid to provide more leverage, and a stationary base to hold the jar. The base ultimately was similar to his original concept, including the use of a suction cup to hold the base to the kitchen counter, though the mechanism of tightening to the jar was different. At the 13-minute mark, he stopped designing and conducted a design review to evaluate his solution-in-progress (section e in Figure 12). This evaluation process led to some refinements/additions to his list of requirements for his solution; like the requirement that the device must provide better leverage than just the jar lid alone (a perceived failing in his second concept). While he was refining the requirements, Oscar verified the level of detail required for this design activity, and then went back to his first concept to think about it further. This line of thinking led him to make an assumption on the reasonable range of jar sizes that his design would accommodate.

Starting at the 18-minute mark, Oscar began designing a third concept that focussed on increasing leverage when turning the lid (section f in Figure 12). Oscar again struggled to think out loud while sketching his concept, even saying: “I'm just doing some sketching. I'm not really thinking about much right now. I’ll show it to you after I’m done.” As he presented the design, he added in a few details that he missed, but he did not vocalize any decision-making or evaluation for this concept, just presenting it as though it were finished. Once he was finished presenting this concept, he started thinking about an additional device that could be used to break the seal on the lid to make it easier to open but did not integrate it into his existing designs. At the 25-minute mark, Oscar switched to thinking about the base again (section g in Figure 12). This time, his design was similar to the third concept for grabbing the lid, relying on two screws (one on either side to clamp on to the jar). During this time, he would occasionally verbalize what he was drawing, but did not communicate any detail about the decisions he was making, or how he arrived at that concept. These designs were also lacking in any specifics like dimensions or materials, and just focussed on the general concept of the device. Around the 27-minute mark, Oscar went to the internet to see more detail on heavy duty suction cups. As with his first online search, he did some evaluation of the different suction cup designs, focussing on ease of use for a person with only one hand. Even though he has thought about the user only having one hand to operate the device throughout the design activity, his third concept would be very awkward to operate single-handed, having a tightening screw on opposite sides of the jar.

Beginning at the 30-minute mark, Oscar began working on a refined concept for the portion of his device that would attach to the lid and provide the user with additional leverage (section h in Figure 12). This concept had more of an emphasis on ergonomics in the handle design but was fundamentally a refinement of the third design concept. With this final concept, Oscar lost sight of the requirement that the user must be able to install the device with only one hand; his device would be very challenging to install for any user, single-handed or not. At 38 minutes, Oscar shifted focus to the base of the device to finish his design activity (section i in Figure 12).

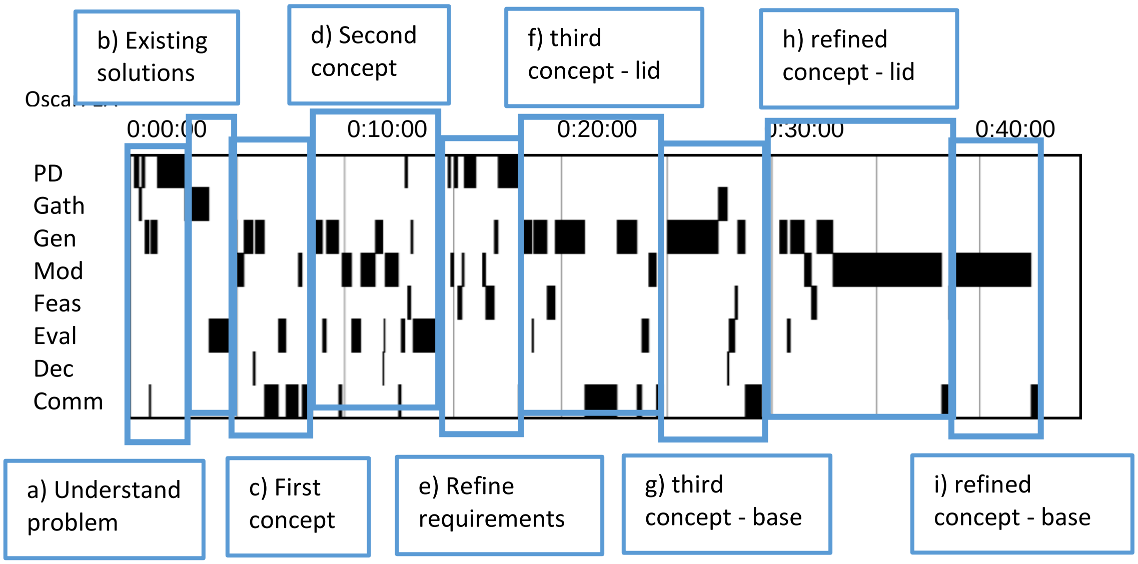


Figure 48 Overview of design process, 1A interview with Oscar

Patrick

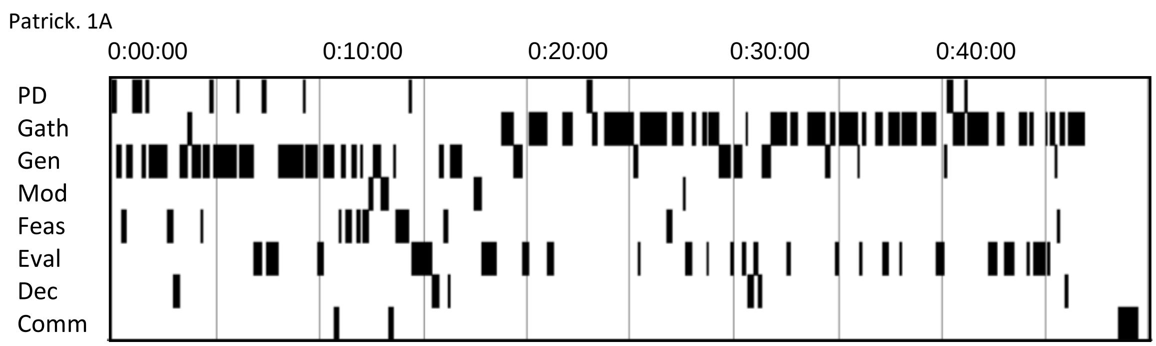


Figure 49 Design timeline of 1A interview with Patrick

Patrick's initial framing of the problem was to create a device that could act as the user's missing second hand (section a in Figure 13). The first sub-function that he thought through was how to hang on to the jar and how different jars will be relatively easier (hexagonal shaped) or harder (round) to hold securely. Patrick did not struggle with the act of thinking aloud the way that some of the other participants did, however he seemed to struggle with the artificiality of the task and the environment he was solving it in. He would talk about tasks or uncertainties in a very abstract way. For example, early on when thinking about the types of jars a person can interact with, he talked about the need to do some research without actually doing it: "I also have to think about the size of it too like what's the most common size of jars. I'm sure there [will] be some research for that." After thinking about the part of the device that will hold the jar, he moved to the connected function of how to hold the device stationary so the user can unscrew the cap. When thinking about possible solutions for this sub-problem, he quickly turned to his experience with woodworking and took inspiration from a common clamp shape (an "f-clamp") with some modifications (like softer jaws to hold on to round jars). At this point, about 3 minutes into the design activity, Patrick had the beginnings of a concept, but unlike most of the other participants, he resisted writing down or sketching anything, instead keeping everything in his head and just talking about things as they came up. His initial concept was a prosthetic arm of sorts with a clamp on the end where the user would pin the device under one arm and open the jar with the other hand.

After developing the initial concept, he shifted to brainstorming other designs that could also solve the problem, coming up with solutions like a mechanical iris that could hold the jar. During this process, he was also refining the requirements for his device (section b in Figure 13). During this portion of the design activity, he shifted his framing to a portable device that could sit on the kitchen counter. He struggled to think of a way to keep this portable unit stationary on the counter as you took the lid off, and so he drifted back to his original solution concept. At this stage, his early evaluations tended to revolve around the costs of the device. At the 11-minute mark of the activity, he brought up an alternative clamping device for holding the jar: a band or strap clamp (section c in Figure 13). This similarly drew on his knowledge of wood working, as these are common clamps for holding frames of various shapes together. After talking through this new method for holding the jar, Patrick returned to the sub-problem of holding the device and jar steady. At 12 minutes, Patrick reflected on whether this new solution solved the original problem and realized that he may have issues with a user installing this new clamp on to a jar with only one hand, so he acted out the movements of tightening the clamp with one hand. Returning to the problem of holding the device steady, Patrick stayed with his initial idea of having a long enough handle where you could hold the device and jar in your arm pit. With that concept firm in his mind, Patrick returned to a business analysis of the device, attempting to answer questions such as: is it cost effective to make? Is that woodworking clamp design patented?

At this stage, he started thinking through more of the details of the design, but again returned to thinking about this in a very abstract way (section d in Figure 13). When thinking about the number of points of contact between his clamp and the jar, Patrick commented: “We'd have to test like the jar sizes and stuff and see the smallest jar. Obviously, I don't want the plastic parts that interfere with the clamping force of the of the strap, so we say that that would just be through testing, but say arbitrary number. We pick four for even the smallest jars.” Around the 17-minute mark, he starts to get lost in the complexities of designing a device within a company: “I'm thinking now of like who's going to be in my team, like I don't want to outsource many of this. Obviously, it's it's my job to design this, but would I have to consult somebody like in ergonomics? or … I’m not sure how big of a problem or how much budget would be in my like R&D for this? But if I don't have to consult anyone outside, that would be nice, but if I do, who would? Who would I have to? How much time would it take for them? Is it really worth it making it?"

Shortly after the 18-minute mark in the design activity, Patrick felt like his design had concluded and he asked if that was good enough. After hearing a confirmation that he can end the design activity whenever he thinks his design is finished, he went to the internet to search for information to help him solidify some of the design and manufacturing details (section e in Figure 13). His online search started with looking at existing strap clamps and their prices. Through the first 3 minutes of his online search, he was refining in his mind the size and design of the various features of his clamp as compared to ones built for woodworking. At 24 minutes, his search shifted into manufacturing methods, namely injection molding (section f in Figure 13). Patrick struggled a bit to find useful resources to help in refining two components of his design that he was concerned with: the jaws which contact the jar, and the handle that the user will clamp under their arm. These resources included much information that wasn't useful to Patrick, but he was able to make a few refinements to the shape based on what the manufacturing method would allow in the final part. At the 33-minute mark, after he had been spinning his wheels on manufacturing for a few minutes, Patrick was informed that he doesn't need to worry about detailed manufacturing methods for this design problem, just focus on the design of the device.

At 35 minutes, Patrick went back to the pictures of existing band clamps so he could understand how they are put together in more detail (section g in Figure 13). After spending about 2 minutes with that, he went back to search for alternative manufacturing methods (section h in Figure 13). At the 40-minute mark, Patrick produced one more requirement for the device: it should fit in a standard kitchen drawer. Around 43 minutes, he talks about some of the challenges of finding suppliers based on his experience in woodworking: "What are the actual costs of injection molding? I won't know that until I until I'm in the field. I won't know. Maybe the company has certain connections in that change things I know like woodworking. Who's your supplier changes a lot of things what you can get what you can't get, but I know this is like an open-ended design thing." Figure 13 below shows the annotated overview of Patrick's design process.

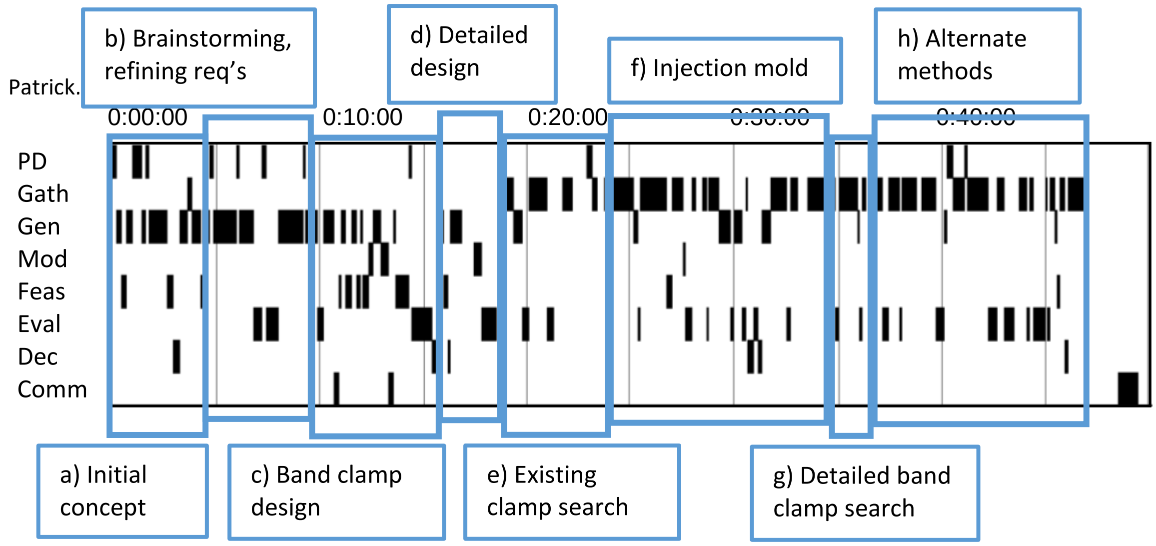


Figure 50 Overview of design process, 1A interview with Patrick

Jill

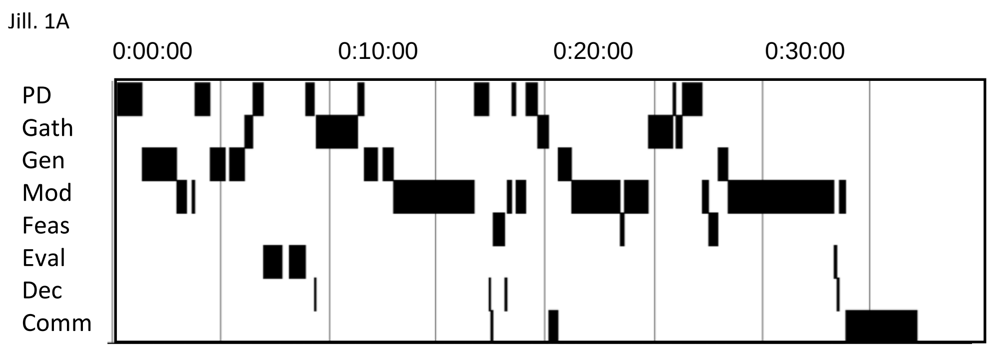


Figure 51 Design timeline of 1A interview with Jill

Jill started by listing some requirements for her solution (for example, it will have to adapt to different sizes of jars). After listing a couple requirements, Jill transitioned to developing a rough solution to the problem (section a in Figure 52). This first solution took the form of a "claw machine" that could grab on to the lid (her sketch of the device resembled the claw machines that are frequently in arcades). She then used that solution as a means of refining her understanding of the problem itself (section b in Figure 52). During this phase, Jill was debating whether to require the user to use their hand to hold the jar, or to have the device do it, though ultimately, she delayed making this choice and just wrote some requirements for the solution. As part of this debate on the general approach she wanted to take, Jill made an assumption about her users' general physical abilities (that they have one working hand). Jill's initial round of evaluations at the 8-minute mark were assessing the general accessibility and cost differences of her initial two concepts, though she didn't elaborate on how she was evaluating these differences in the concepts beyond an intuitive understanding of the devices. Around the 10-minute mark, Jill went to the internet to find the general sizes for jars you would find in the kitchen (section c in Figure 52). With that information in hand, she refined her device requirements, before transitioning to the detailed design of her solution.

Jill started with the design of the base of her machine that would hold the jar steady (section d in Figure 52). Her general concept was a rubber strap that would wrap around and hold the jar. This section of the interview was challenging to decipher as Jill frequently stopped talking or would talk too quietly to accurately produce a transcript of the interview, though it was clear that she was working through the specifics of the base of her device in this time.

As Jill continued to work on her solution, she hit a new function that her device had to possess, causing her to go back and figure out what the requirements of the device were before continuing. One example of this occurs from approximately minutes 16 to 20 where Jill is thinking about the part of her device that will grab on to the lid (section e in Figure 52). During this time, she is trying to decide between a claw or a ring-type device to hold on to the lid. At the 20-minute mark, she grabs a large pill bottle from a shelf in her room to examine how it opens and then is asked to show what she has been working on. Her observation of the pill bottle proved to her that there is space to hook something under the bottom of the lid, and so she incorporated this detail on each finger of her "claw" for removing the lid. She chose the claw design based primarily on her intuition of how it would perform and quickly moves on to incorporating that into her design over the next several minutes (section f in Figure 52). At the 24-minute mark, she examined the pill bottle again briefly, which appeared to cement some kind of decision in her mind, and she continued sketching her solution.

At the 25-minute mark, Jill went back to the internet to verify the direction jar lids need to be rotated to be removed (section g in Figure 52). The search did not turn up anything useful, and so Jill went and grabbed another jar from a shelf in her room and verified that the lid comes off the same way as the first one she grabbed; and so Jill made the assumption that all jars have lids that unscrew in the counter-clockwise direction. At 27 minutes, Jill went back to the original problem statement to check her understanding of the problem and then asked if the device needs to reinstall the lids as well. Jill went back to her detailed design with the new feature that it would also be able to reinstall the lid on the jar. Jill tested the lid of the pill bottle again at 28 minutes, and then started thinking of ways to stop the jar from rotating as the lid was turned by the machine. During sections f and h of the design activity, Jill would occasionally make a note that a motor should get installed in a specific location on her device. At the 30-minute mark, Jill added in a battery as the power source of her device. With this last detail sorted, Jill worked on a clean sketch of the entire design. During this time, Jill mostly went over details that she had already mentioned, though some final material selections were made as she sketched the final design. Jill's final design included a stationary base that held the jar with an articulating arm that ended in a claw which would grab the lid and twist it off. Jill ended her design exercise with a final presentation of her design to the interviewer (section i in Figure 52).

Analysis

Jill spent 37 minutes and 15 seconds completing the design activity, 6 minutes less than the average time (see Figure 52). While designing, Jill transitioned across design steps 40 times – a rate of 1.1 transitions per minute, or nearly half the average rate of the other participants. Jill was talkative and projected her voice well through the first third of the interview, but once she started the think aloud design activity, Jill got very quiet. Throughout the design activity, Jill struggled to vocalize her thoughts and had to be reminded regularly to continue speaking out loud. When she did speak, it was frequently very quiet, and was mostly speaking to herself. This made the construction of her timeline a challenge, and likely introduced error to the process. This makes it likely that her transition rate was higher than 1.1 transitions per minute, but some transitions may have been lost due to her difficulties with vocalizing her thoughts throughout the activity. Jill was the second last student to be interviewed (on Sept. 29), which means she had received approximately 3 weeks of instruction in ME 100 before her interview.

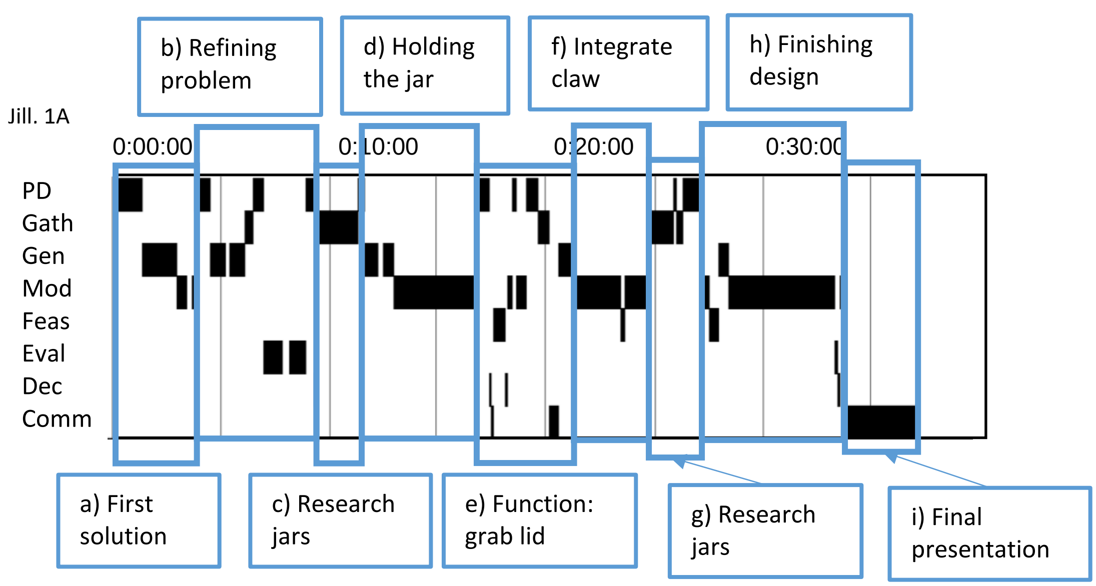


Figure 52 Overview of design process, 1A interview with Jill

Table 63 shows the percentage of her total time that Jill spent in each design step. She spent the most time in modelling, with comparatively little time in feasibility analysis, evaluation, and decision-making.

Table 63 Percent of time spent in each design step during 1A interviews, Jill highlighted

Design Phase	Chris	MJ	Jay	Bond	Oscar	Patrick	**Jill**	Michelle
Problem Definition	10%	6%	9%	12%	8%	4%	**15%**	1%
Gather Information	1%	13%	17%	8%	4%	33%	**12%**	14%
Generate Ideas	8%	20%	12%	13%	26%	22%	**14%**	17%
Model	37%	23%	26%	19%	29%	2%	**38%**	38%
Feasibility Analysis	10%	7%	16%	6%	4%	5%	**3%**	3%
Evaluation	1%	4%	10%	2%	10%	15%	**5%**	5%
Decision	1%	2%	2%	1%	0.4%	3%	**1%**	4%
Communication	23%	18%	8%	23%	14%	3%	**10%**	10%
Transitions (mean=83)	50	148	64	112	75	112	**40**	62

Reflecting on the behaviours of a beginning designer described by Crismond and Adams, Jill showed a mix of beginning design traits, and traits of a more experienced designer:

- Jill spent time understanding the requirements for the device, used an early idea of a solution to refine her understanding of the problem, and continued to revisit her framing of the problem throughout the design activity,
- Jill researched jars, their sizes, and how they operate, but did not do any searching for design alternatives or existing solutions,
- Jill generated 1 or 2 ideas for each of the major components of her device,
- Jill conducted no tests of her proposed ideas beyond verifying the operation of a bottle lid,
- Jill designed a device that was missing a lot of detail, especially in the electro-mechanical aspects of the design, but which would be fully operable by someone with only one hand,
- Jill made decisions with no evaluation, relying on her intuition, and
- Jill developed a single design concept and included no iteration or reflection while designing

Overall, Jill's process appears to fit the cascade shape described by Atman, though she only spent a third of the available time. As with Oscar, Jill's early process appeared similar to the method of "solution conjecturing", or co-evolution of problem and solution spaces (Dorst and Cross, 2001; Dorst 2019).

Table 64 A summary of Jill's prior knowledge, adapted from Table 17

Prior knowledge	**Factual**		**Conceptual**		**Procedural**	
Relevant factual/conceptual; limited procedural knowledge	Programming Airplanes Crafting	Medium Low Medium	Programming Airplanes Construction	Medium Low Medium	Software design	Medium

Connecting these observations to how Jill described her prior experiences, her design process seems to match her descriptions of past design activity. In the past, Jill has relied on a trial-and-error approach to identifying shortcomings in her design and has relied on physical prototyping and testing for her iteration. She has not yet developed other methods for testing and/or evaluating designs, nor for making reasoned decisions. She seemed to be comfortable with the ambiguity of the design problem, however, and her methods for framing and re-framing the problem were more advanced than a beginner, which fits with her past experiences. She has gone through several design-build projects with competitions like Science Olympiad in the US and has developed an effective approach for resolving some of the ambiguity at the start of the design process. Beyond this early part of the process, however, Jill has not yet developed the tools expected of an engineering designer.

Jill's prior factual and conceptual knowledge did not seem to be employed in her design. In addition, unlike many of the other participants who kept their solution firmly in the mechanical realm, Jill included a motor in her design, taking her further into domains that she has little background in. Unfortunately, Jill did not seem to be aware of what it would take to incorporate a motor or motors into the mechanical design of her device, nor the electrical requirements of including it. It appears that she made this problem into a multi-disciplinary problem and didn't have the knowledge of the new domain (in this case electrical, or electromechanical) after it was introduced. She was somewhat conscious of this early as she debated trying to keep it to a purely mechanical solution, though she was largely concerned with cost at that stage. She did include some of the other components that would be important to this system, like buttons, but little else.

Michelle

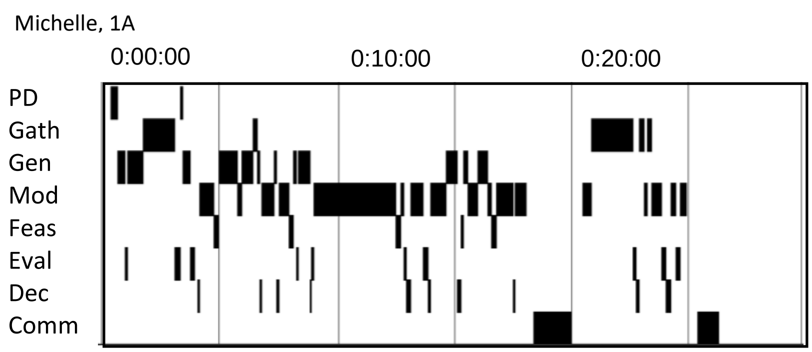


Figure 53 Design timeline of 1A interview with Michelle

Michelle's initial time spent on problem definition was spent on repeating the design prompt, after which she jumped into a brainstorm about how to grab the lid and how to power the device (section a in Figure 14). Unlike many of her peers, Michelle went to the internet to see what devices already exist to help with this task (section b in Figure 14). She had in her mind early that the device should be electrically powered and so she searched for powered jar opening devices and found one that she liked.

After finding a device that she liked, Michelle began sketching the design for her version of it (section c in Figure 14). While she was working on the initial concept of the device, she was envisioning herself as the user, acting out the operation of the device she had in mind. As she continued to think about the concept, and act out its operation, she would confront an issue with her design, intuit a solution to the issue, and keep moving forward with the development of the concept. During this section of the activity, Michelle did little writing; she mostly talked through each issue as they came to mind. Around the 9-minute mark, Michelle started sketching the concept and began making decisions on details of her design, like the buttons/switches required, the minimum size of jar her design would accommodate, material selection, etc. (section d in Figure 14). Michelle would occasionally pause and act out the operation of her device, helping her refine how the user would interact with it.

Michelle completed the majority of her design in under 20 minutes before giving an overview of her solution at the interviewer's request (section e in Figure 14). Her solution looked very similar to the design of the device she saw online, except with 4 contact points with the jar instead of 2. Her device clamped on to the jar from the top, had outer grips that held the jar, and an inner motorized grip that spun off the lid. At the 20-minute mark in the design activity, Michelle indicated that she was finished the design, before realizing that she had not specified the electrical components very well (section f in Figure 14). Michelle admitted that she didn't know much about the electrical components she would need, and after thinking briefly about what her design would require, she jumped back to the internet to verify her understanding of the details of jars like the direction of rotation to remove the lid (section g in Figure 14). During her search online, she commented on the general reliability of the information she was reading, which was not typical of the other participants. Michelle's research led her to add a button to her design which can change the direction of rotation from counterclockwise to clockwise (section h in Figure 14) to allow the user to use the device to put the lid back on as well. With this final adjustment to her design, Michelle declared she was finished. The design activity ended after Michelle was requested to walk through her final design. Figure 14 below has an overview of Michelle's process.

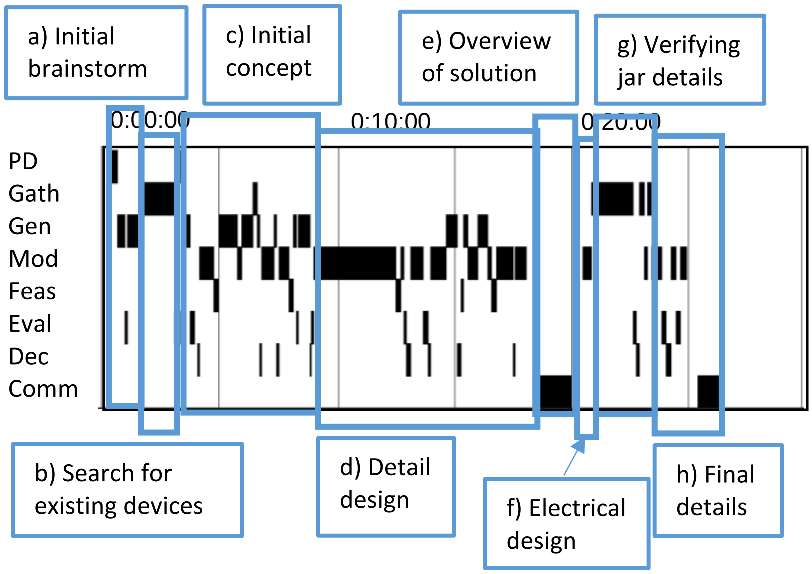


Figure 54 Overview of design process, 1A interview with Michelle

Appendix E Detailed Data – Student Experience Prior to 1B

Michelle

When asked how her 1A term went, Michelle commented that she had to learn time management skills that were more appropriate for the university environment, and that she struggled with finding the time to do all of her regular assignments by their deadlines. Michelle also commented that she was not able to really complete any work for the formula motorsports student team that she joined in 1A as she grappled with the workload and adjustment to university life, but that she was prepared to spend more time working for the team in her 1B term. Michelle commented that ME 100 was the only course where she felt she learned anything related to design, and that it was a very different sort of course from her other 1A courses. Michelle felt that ME 100 gave her the experience of what engineering would actually be like, as compared to her other courses which she felt were just "setting you up for engineering". Michelle was surprised at the significant quantity of design experiences she had in ME 100, and credited the course with shifting her understanding of engineering from a discipline that is concerned primarily with knowledge of physics and math, to one where design is a central feature of the discipline.

In follow up questions about ME 100, Michelle remembered the lectures on design, and remembered learning about, and applying, the concepts of criteria and constraints at various points during the term. At this point in the interview, she would occasionally mention the concept of functional requirements (a concept taught in ME 101 in 1B) before reminding herself that she was thinking about the wrong term. The only activities that Michelle mentioned by name were the coffee maker dissection activity, the cell phone stand project in EGAD, and the toy project. Michelle happened to have her 3D printed cell phone stand on her desk. When discussing it, she mentioned the process that was described by the EGAD instructor (viz. concept sketches followed by a SolidWorks model where the centre of gravity was calculated before 3D printing) and was quite proud of the aesthetics of her design. She also commented that she spent some time on her own continuing to work on her cell phone stand design; trying to incorporate interactive buttons in the stand that a user could fidget with.

Michelle's toy project was a collectible toy that would launch a disk with a hidden character in it. When the disk landed, it would open and reveal the character inside. From her description, there were really two components that they had to design: the launcher, and the disk which contained the character. For the launcher, they found existing designs that formed the base of their solution, and so much of their effort was centered on the character disk portion of the project. Michelle mentioned that their toy project did not contain any of the electronics that some of her peers' projects did; their solution was purely mechanical, relying on springs to deploy the hidden character. When asked what part of the project she contributed to, she mentioned that they split the tasks based on their perceived strengths, with the strongest group member leading that task, with the others supporting. Michelle selected the task of writing the report; letting her teammates lead the sketching, design, and construction tasks. From this, it is difficult to know exactly what she contributed to the design, however she seemed to have a good understanding of how the project was constructed. So, while Michelle may not have been as involved in the design and construction of their project as some of her teammates, she did mention that concept selection and deciding on the criteria and constraints of their project were done collaboratively as a group. When asked to elaborate on what the toy project taught her about design, she emphasized the lesson of not starting a design process with a solution in mind; that finding and understanding the problem comes first.

The last experience that Michelle mentioned was programming related: Michelle mentioned that she attempted to make a Rubik's cube solver in Python for a simplified 2x2 cube.

Jill

Recapping the 1A term, Jill found physics to be the hardest course, while much of calculus, chemistry, and algebra (to a lesser extent) were reviews of her high school courses. Like Michelle, Jill felt that ME 100 gave her a good taste of what mechanical engineering was going to be like, and she found that she really enjoys designing in CAD and solving problems. When asked about the course, the toy project and the cell phone stand were the two primary experiences that Jill brought up. Jill remembered lectures on constraints and criteria, and at various points in the interview would talk about her design projects using these concepts. For Jill, AutoCAD and SolidWorks were totally new to her prior to her 1A term, and it was these technical skills that stood out in her mind as the main learnings from EGAD. She also mentioned learning some tips and tricks of design, but the CAD tools were primarily what she took away from the course. For DCAP, she described it as learning how to think like an engineer, and how to go through the design process.

In the cell phone stand project, Jill struggled to meet the materials constraint of the project given to her by the EGAD professor. She mentioned that she had to go through more than a dozen iterations as she refined the design and reduced the 3D printed material requirements of her solution. With Jill's phone stand, she attempted to make a recess in the top of it to hold her smartwatch, and attempted to make a versatile stand that would work for more than one type of phone. She was happy that her phone stand was successful in meeting this design criteria; she commented that it could also hold up her tablet without becoming unstable. With this project, the primary lesson she learned was to really think about the user's needs before deciding on a solution. She was able to see some of her friends' designs and had discussions with them about the different aspects that they chose to emphasize. Through these conversations, and reflections on her own design, she came to see how paying attention to a product user's needs could lead to very different solutions to the same problem.

Jill's toy project was a hammer that could only be picked up off its pedestal if the user was wearing the bracelet that acted as the key. The team relied on magnets hidden in the hammer handle, and in the bracelet to interact so the handle could be rotated and unlocked from the pedestal. For Jill's project, one of her teammates was online; he lived several hours away from campus and only came in-person near the end of term after completing some surgery. To meet the demands of the project, the team split into 2 groups of 2, Jill and her friend worked on the bracelet and hammer handle, while the other two worked on the pedestal design. Jill was heavily involved in all phases of design, manufacturing, testing, and refinement of the bracelet/hammer handle components of the project; commenting that it was her first time in the machine shop, something that she really enjoyed. While they had a SolidWorks model of the handle that could have been 3D printed, they ended up making it from scratch using household materials like PVC pipe and wooden dowels. Jill commented that because of the challenging work arrangements in their group (with one member off campus), they felt behind in the execution of the project, and so just started working on the prototype with limited advance planning. Jill felt that her group pre-emptively jumped to a solution to their problem that used electro-magnets, and they lost time as they attempted, and ultimately failed to incorporate them into their design. The mechanism they settled on ended up being challenging to construct, and the group were working right up until the symposium to complete a working project.

In November of her 1A term, Jill joined the UW Orbital team. This team is working on the design and construction of a CubeSat, which is a 10cm x 10cm x 10cm satellite. Jill joined the mechanical CAD sub-team, and as part of this experience, took part in training in the student machine shop, a 3D print lab, and with the older members of the team. Jill mentioned that the mechanical lead designer was an upper year student in Mechatronics Engineering who had been very supportive of Jill's learning and development in the team. Jill would work on design tasks and would receive feedback from this upper year student to improve her designs. Through this team, Jill also received some exposure to Finite Element Analysis in SolidWorks to evaluate the mechanical strength of her designs. She mentioned that was looking forward to learning more about materials from her 1B course on the subject, in parallel with learning more FEA from the Orbital team. At the time of the interview, Jill's design had not yet been manufactured, so she had not yet seen her designs produced in the real world. Prior to her 1B term, Jill also designed a spinner ring fidget toy, and she was looking forward to 3D printing her design as part of her training in the 3D print centre. The ring was designed in SolidWorks, and used the assembly and animation features to verify it would be able to spin once it was manufactured.

Analysis

Table 65 summarizes Jill's knowledge development up to the point of her 1B interview. Experiences from ME 100, university side projects, and the UW orbital team have enhanced Jill's existing knowledge in several domains including 3D modelling and simulation, and manufacturing methods including rapid prototyping and machining.

Table 65 Updated knowledge development from experiences - Jill

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Knowledge of beginner/intermediate software engineering concepts	AP computer science course in high school	6. Create - producing
	Limited knowledge of airplane concepts, materials, and individual components	Science Olympiad competition in grades 9/10	5. Evaluate – critiquing
	Knowledge of common crafting materials and tools	Science Olympiad; ME 100 projects	6. Create – producing
	Limited knowledge of materials, design tools, and construction tools relating to 3D printing	ME 100 cell phone stand; university side project; university makerspace training	2. Understand - Explaining
Conceptual	Knowledge of beginner/intermediate software engineering principles	AP computer science course in high school; experience in a hackathon	6. Create - producing
	Limited knowledge of airplane assemblies	Science Olympiad	6. Create – producing
	Knowledge of common construction methods	Science Olympiad; ME 100 toy project; UW Orbital student team	6. Create – producing
Procedural	Knowledge of beginner/intermediate software engineering processes	AP computer science course in high school	3. Apply - Implementing
	Knowledge of manufacturing with 3D printers	ME 100 cell phone stand; university side project; university makerspace training	2. Understand - Explaining
	Limited knowledge of machining and manufacturing processes	University makerspace training	2. Understand - Explaining
	Knowledge of 2D/3D CAD modelling, and simulation	ME 100; university side project; UW Orbital student team	5. Evaluate – critiquing

Patrick

During Patrick's 1A term, he was competing in a varsity sport at the university, which required significant time each week. He commented that it was "an uphill battle to pass some classes" after his midterm results came back, but he was successful in passing the term and making it to 1B. He was looking forward to his 1B courses more than 1A because they felt more related to engineering, and he was generally more interested in their content. Like Michelle and Jill, Patrick could not identify any design learning in 1A outside of what happened in ME 100; and his recollection was that most of the teaching and learning of design was in DCAP. His recollection of EGAD was very focussed on the CAD, and especially the SolidWorks skills that were taught in that section of the course. From DCAP, Patrick learned about criteria and constraints; this concept really seemed to stick with him as he repeated it a couple of times during the interview. Patrick also recalled learning a few different design processes from DCAP including the PRIMED design process that was mentioned earlier. The only projects or activities that Patrick mentioned were the toy project, and the cell phone stand project (when asked about it). He didn't mention, or perhaps failed to see, how the other learning activities in ME 100 related to design.

Patrick's toy project was a box full of water that could generate a large wave, simulating a tsunami. The user would design a small structure, or structures, and place them in the box to see if they could survive the impact of the wave. For the project, Patrick was involved in the decision-making processes of the team, but his primary contribution was to construct the box and the piston that would generate the wave. Patrick was able to utilize his home woodshop to construct the wooden components for the project as it is located relatively close to campus. When asked what the project taught him about design, Patrick commented that it developed his teamwork and collaboration skills, and his ability to break a big problem down into smaller, defined pieces. For Patrick's cell phone stand, unlike most students in EGAD who were only permitted to print one copy, Patrick was able to print a first version, make changes, and print a second updated version because he used his own printer at home. The changes were necessary because his original design was unstable when a phone was placed in the stand in a vertical orientation. From this discussion, it is not clear if he calculated the centre of mass in SolidWorks as was mentioned by the other students and the instructor.

Patrick did not participate in any engineering-related extra-curriculars in his 1A term; no student design teams, or events like hackathons, as varsity sports consumed his time outside of classes. He was able to complete some small 3D printed designs for his home wood shop during the 1A semester, and especially between the 1A and 1B terms. Through these projects, he was able to leverage the SolidWorks skills that EGAD taught him, in combination with his personal 3D printer.

Jay

Jay characterized the design teaching in ME 100 as learning design principles including problem criteria and constraints, plus the social impact of design from the DCAP portion of the course; and the "nitty gritty of actually designing" using CAD from EGAD. Jay was able to recall most of the PRIMED design process that was taught in DCAP, even though he didn't refer to it by name, and recalled the toy project as the most significant design experience in the 1A term. With some prompting, Jay remembered the cell phone stand project as well; and mentioned that there were other weekly assignments where he completed quick designs, but he didn't feel those were substantial enough to warrant discussion.

Jay remembered more details of the cell phone stand project than Chris did; Jay recalled using SolidWorks to find the centre of mass of his design, verifying that it would work for its intended purpose before it was printed. Jay also felt that there was not much room for iteration in this project because he only had one chance to print the design. He did not talk about the earlier rounds of feedback/iteration with the teaching team prior to printing and seemed to have fewer issues with meeting the project constraints than Chris did.

For Jay's toy project, he and his team created a game for 2 players to test their relative reaction time. The slower person to respond to a visual cue by pressing a button was sprayed by a water gun. Their project incorporated electromechanical elements including motors and a programmable controller. Jay's responsibility was the design and construction of the enclosure for the entire system. Jay's process for designing and building the enclosure was to make a couple prototypes of the design, prior to a final SolidWorks model, and 3D printing. Ultimately, they were not able to use the enclosure in their final prototype as it would not fit all the components in their project, and given its size, it would be difficult to iterate on the design and print a second one in the time they had for the project. For Jay, the main learnings from the toy project were communication within a team and developing trust with his teammates.

In his 1A term, Jay joined the formula motorsports team in their aerodynamics sub-team. In the fall term, he helped complete some of the molds for creating their custom carbon fibre aerodynamic parts, and then helped the team with laying down the carbon fibre to make the parts. Installation of those parts on the car was scheduled to happen during his 1B term, but it was not clear if that process had started yet when he was interviewed. In his 1B term, Jay opted to focus on the Computational Fluid Dynamics (CFD) simulations that the aerodynamics team were using to optimize their designs. At this stage in his time with the team, he was only carrying out the simulations, and was not directly involved in the design choices – these were being made by upper year undergraduates on the team – but he felt the CFD simulations were aiding him to understand the process of design, especially in a large team environment. These upper year students were meeting with Jay weekly to discuss his progress and help him with conducting his work. Jay did not participate in any other design teams or design events in his 1A term.

For Jay's winter co-op work term, he worked as a test and validation engineering co-op for an automotive parts supplier. Jay's role was to set up and conduct tests of the company's parts to ensure that they adhered to standards. Jay described this work as designing the systems to test parts, not designing the parts themselves. Jay was given a part and a specific feature to test, and he would have to identify the components needed to test that feature, construct the test setup, and conduct the test; the design and construction of these test setups would typically take a few hours. His supervisor would check in before he conducted the test to ensure it was appropriate for the task at hand. This experience was "a real eye opener" for Jay in seeing how engineering works in a real company. He was surprised at the rigor involved in designing, testing, and refining new designs. When asked to reflect on how he has changed since his first interview, Jay felt more comfortable talking with supervisors and professors.

Analysis

Table 66 summarizes Jay's knowledge prior to the 1B interview. Jay seemed to have benefited from his work term experiences designing and implementing validation tests, his various experiences with the engineering student design team, and his toy project. Like Chris, Jay needed some prompting to remember some of the design activities in ME 100, like the cell phone stand project. As expected, their recollection of the teaching activities in 1A was definitely weaker than the 8-stream students. Other than the CAD skills which Jay has continued to develop in the student team, it is interesting that it is professional skills like teamwork and communication that Jay felt he had developed the most in his time at university.

During the discussion with Jay, he seemed to benefit from seeing physical prototypes of his designs. Based on his descriptions of the toy project and the cell phone stand project, he may have struggled with iterating on designs, identifying their faults, or areas for improvement, when using only design tools like sketching or SolidWorks.

Table 66 Updated knowledge development from experiences - Jay

Knowledge type	Level of experience by domain	How developed	Cognitive Process
Factual	Knowledge of 3D printing	High school course project; ME 100 cell phone stand and toy project	3. Apply - Executing
	Knowledge of electronic circuits and actuators	High school course; ME 100 toy project	4. Analyze - Differentiating
	Limited knowledge of composite materials	Waterloo automotive student team	2. Understand - Explaining
Conceptual	Knowledge of electronic circuits and their layout and construction	High school course; ME 100 toy project	6. Create – Producing
	Knowledge of knowledge of common components of mechanical design	ME 100; co-op work term	6. Create – Producing
Procedural	Knowledge of 3D CAD modelling and simulation	High school course project; self-learning with videos & projects; ME 100; Waterloo student team	3. Apply – Implementing
	Knowledge of manufacturing with 3D printers	High school course project; ME 100 cell phone stand and toy project	3. Apply - Executing
	Knowledge of constructing circuits and verifying their operation	High school course; ME 100 toy project	3. Apply - Executing
	Knowledge of design processes	ME 100; co-op work term	3. Apply - Executing
	Knowledge of design verification processes	co-op work term	3. Apply – Implementing
	Limited knowledge of manufacturing processes of composite parts	Waterloo automotive student team	3. Apply – Executing.

Oscar

Oscar described the design teaching in ME 100 as primarily lecture-based learning in DCAP, however Oscar had a better memory for the course contents of ME 100 than virtually all of the other participants. This included recognizing that activities like the coffee maker dissection and paper rocket activity were meant to teach them concepts related to mechanical engineering design. He clearly remembered learning about criteria and constraints and applying those concepts in the design process of the toy project. Oscar characterized the EGAD portion as guided practice to learn CAD tools as well as practical tips and useful anecdotes from the EGAD instructor. Like most of the participants, Oscar found the two parts of the course felt quite separate; and felt that there were not many opportunities to practice designing in ME 100 outside of the toy project.

Oscar's toy project was a tower building game that included simulations of physical phenomena like earthquakes to try and knock down your structure. The tower constructions were made using existing, off the shelf construction toys, so their project was to construct the moving elements of the simulation. Oscar's contribution to the project was to design and construct the spinning mass portion of the design that powered the simulation as well as to write the report. From Oscar's comments, there was clearly some tension between him and his teammates, and since Oscar recognized that the report was where the marks were focussed, he wrote the full first draft without much input from his teammates. From this project, Oscar learned that engineering design is more methodical than the process he had used in his side projects in the past; that relying on intuition alone is not what is expected in engineering because of the risks (safety and otherwise) to users of the design.

Oscar also recalled the cell phone stand project and had his 3D printed stand on his desk during the interview. Oscar remembered using SolidWorks to calculate a centre of mass for his design to ensure it would be stable with his phone installed in it and was satisfied with its performance. Oscar felt that this project was more of a "homework project" where he spent as little time as possible completing it, and he didn't think it taught him much about design. Oscar did mention that the main feedback he was hearing from the TAs (on his design, and with his classmates) was around how to design a part that could be successfully 3D printed. Oscar did not participate in any extra-curricular activities in his 1A term, focussing instead on his studies.

Oscar's co-op work term was with a makerspace on campus. In this role, he was responsible for helping students and faculty members who came into the space and was responsible for keeping the equipment and tools in the space in good working order. This frequently meant making repairs to equipment like 3D printers, and with giving advice to users of the space on how they can improve the manufacturability of their designs. Oscar did not think there was much design in this role, though he did describe some conceptual designing he conducted with a professor who was trying to create a new testing machine. Oscar mentioned that he was required to learn some programming languages like Visual Basic in Microsoft Excel and Python to support some course projects that his group was supporting that term. Other than that, Oscar felt the work term required him to learn new things, and learn them quickly; and so he walked away with the mindset that you always have to be willing to learn new things while working. His other learning from the experience was how to work with other people; he described several situations where he had to navigate unrealistic expectations and/or bad behaviour from the various users of the space.

During his winter work term, Oscar described a long-term personal project that he was slowly designing and manufacturing: an Antikythera mechanism. This is an ancient machine to mechanically calculate various astronomical phenomena, that he learned about through a series of YouTube videos he found while in high school. During the winter term, he expanded on his past research of the device to design it in SolidWorks and began manufacturing it using 3D printers and laser cutters. This process was no doubt enhanced by his work term where he was working with these rapid prototyping tools on a daily basis. When asked what he learned from these side projects, Oscar felt they taught the practical sides of design; compared to the more conceptual nature of assignments in courses like ME 100. When thinking about the Antikythera mechanism, he described learning the hard lesson of tolerancing with manufacturing parts that need to physically interface with each other. At times, he would have to produce parts multiple times as he refined the fit between neighbouring parts.

MJ

MJ found the content of ME 100 to be very useful during his winter co-op work term. He felt that the lessons taught in both EGAD and DCAP helped him succeed in his work term and present himself as more capable to his employer. The CAD skills taught in EGAD were the most important learning from ME 100; MJ relied on these skills for his work term. For DCAP, MJ characterized the design teaching as more the theory of design: "the why's and how's, and the design process itself", though MJ found the ideation exercises to promote divergent thinking in a group were useful. MJ didn't seem to remember the PRIMED design process that was taught in DCAP, he instead seemed to prefer the process taught in the Shad Valley program when he was in high school. MJ remembered the concepts of criteria and constraints that were taught in DCAP, and he was conscious of how those concepts were applied in both DCAP and EGAD. MJ remembered the cell phone stand project, and especially how it was an explicit connection between the design process taught in DCAP and the design activity that was happening in EGAD, but he did not end up 3D printing his design, and so the validation step was not performed.

MJ's toy project was a mechanical, jumping frog that relied on mechanisms commonly found in mechanical clocks for its operation. His group was a group of 3, and one of the group members was online only as they were located in another country. When asked what his contribution to the project was, MJ felt that the idea of a toy that simulated an animal was his idea, and he was involved in the prototyping and building as one of the only 2 members in Waterloo, but the design choices were made by the other members of the group. Even after the project, MJ knew the names of the mechanisms that their project used but confessed that he was still unfamiliar with the approach they tried. As with Oscar, MJ felt that the toy project was more about report writing than mechanical design; MJ felt that most of the advice he got from the DCAP instructor related to the project report and not the project itself. MJ mentioned that their project prototype was not very successful in its operation, and he felt the main lesson learned in the project is to think things through before jumping into designing. MJ couldn't think of any other design activities from his 1A term and did not participate in any kinds of extra-curriculars in his first term, as he didn't think he had the time management skills to balance maintaining his grades and the time commitment of a student design team.

MJ's work term was an engineering position with a company that builds devices to monitor pipelines. MJ's role with the company included a variety of tasks including updating CAD drawings, manufacturing and assembly of parts and prototypes, and simple design tasks. During his work term, he was able to learn about Raspberry Pi micro-controllers and the Python programming language, as well as electronic skills like soldering. MJ commented that his supervisor would intentionally give him tasks that he didn't know how to do so that MJ could learn more about it. As one example, one of the projects for the company involved a stepper motor, which MJ did not have any experience with, and so he took the opportunity to teach himself about how they operate. MJ didn't feel like the knowledge taught in DCAP was particularly relevant to his work, but he felt he was able to use his CAD and sketching skills from EGAD during his work term and was able to develop them further while at work. During MJ's work term, he was able to see the parts he was working with in CAD be manufactured and sent out to the field for installation. MJ felt the most valuable knowledge he gained during his work term were the practical realities of mechanical design – the best practices and rules of thumb of the discipline – and he felt that EGAD had provided a good base of this knowledge to build off of. Reflecting back on how he has changed since his 1A interview, MJ gave a similar answer to Oscar: that he is better at slowing down while designing, taking his time with the problem, and not rushing in to solving it.

Appendix F Detailed Data – 1B Design Activity

Michelle

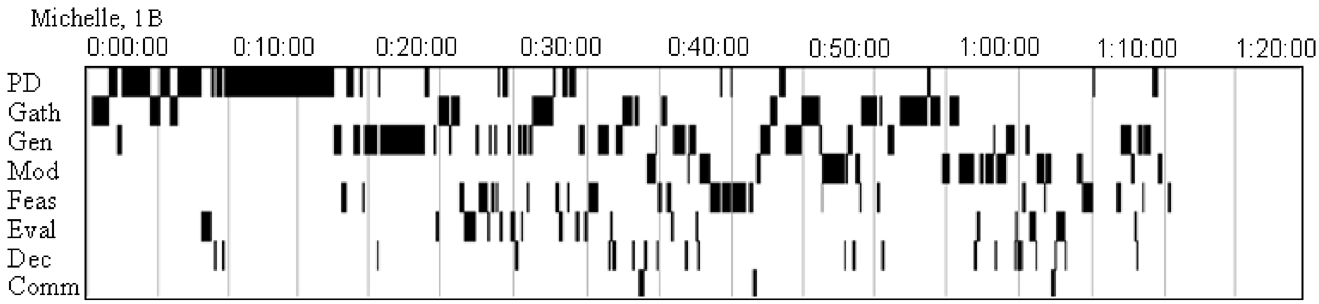


Figure 55 Design timeline of 1B interview with Michelle

Michelle started by researching online what double hung windows are, focussing on the vertical sliding mechanism, and not the tilting feature that many of these windows have. Following that, she started thinking about the requirements for her device. At the 2-minute mark, Michelle identified two main approaches to the problem: a handheld device that is brought to the window, or a solution that is more permanently installed to the window. As she thought about these approaches, she transitioned back to thinking about the problem, posing questions like "how frequently does the window get stuck?". At 3.5 minutes in, Michelle started writing down the open questions that she would need to answer to complete her design (e.g. how does the device interact with the window). Just before the 5-minute mark, Michelle went back to her online search to look at the windows in more detail and try to figure out why the windows stick. This led her to make an assumption that the vertical rails the window slides in must have excess friction to cause the window to stick (perhaps from dirt in the slides). At 6.5 minutes, Michelle began thinking about what her device needs to do, settling on the wording that her device needs to "open the window" as opposed to resolving the root cause of the sticking. She then began writing out the constraints of her device – though she didn't use that term, explicitly (section a in Figure 56). At the 8-minute mark, Michelle evaluated some of the pros and cons of a handheld device compared to a more permanent device on the window. She seemed to be leaning towards a more permanent device, reasoning that if the window sticks once, it likely will again, however she seemed to think the question was asking for a portable one, and so that is what she selected to pursue (section b in Figure 56).

With her general approach decided, Michelle went back to writing out the constraints of her device. Michelle included concerns like cost (e.g. it would be nice if it were inexpensive). After briefly using the language of ME 100, Michelle switched to the language used in ME 101 by writing out the functional and non-functional requirements. Her requirements included that it should be cheap, lightweight, and stable; and that the device will need to exert a force on the window, but not so much as to risk damaging the window itself. At this stage, she attempted to quantify these requirements, though she struggled to define a desired price range and struggled to quantify what stable meant. While thinking about this, Michelle recognized that the device needs to work on a variety of window sizes and types, aiming for compatibility with 80% of possible double hung windows (section c in Figure 56).

Just before the 18-minute mark, Michelle began thinking about what her solution could look like. Near the start of this process, Michelle acted out the installation and operation of her imagined device, identifying some safety concerns to pay attention to as she continued designing. As Michelle thought about her device, she realized it needs to generate a force, and that if the window was stuck fully closed, it might be challenging to install a device that could lift up on the window. Thinking about the force it would need to exert, Michelle decided that she wanted a powered device instead of something that amplified the strength of the user. Michelle quickly sketched an idea for the device where it could hook under the lower window sash with some kind of box applying an upwards force on the window. Michelle didn’t specify where the device would get its power from, or what mechanism would be used to apply the force to the window. As Michelle thought about the device, she added a cushion to the top of the window sash so her device wouldn’t crush the window into the top of the window frame. Just past 23 minutes, Michelle stopped working on her first concept and started thinking about alternative solutions (section d in Figure 56). Michelle’s next family of solutions was focussed on trying to solve the root cause of the stuck window by clearing the window rails. She started by looking for more details of window tracks online and realized that the space in the tracks is typically very small. Her initial idea was a small robot that could travel around the window frame to clean the tracks, but Michelle thought such a small robot would be challenging and expensive to design and build. Michelle also thought about a solution that sprays a liquid into the tracks to clean them out, but she thought that would be challenging to control without spraying chemicals all over the window. She was also worried that stronger cleaning chemicals might damage the window. At 29 minutes, Michelle refined her initial assumption that the window is stuck because of dust/debris in the window track. Just before 30 minutes, Michelle started comparing her two kinds of solutions, commenting that something that clears the dust which might be a more permanent fix, versus a mechanical device that forces the window open, potentially making the situation worse. Michelle thought a device which cleaned the window tracks was a better long-term fix, and so continued to pursue that concept. Michelle quickly realized that there might be an issue getting to the window track to clean it if the window was stuck in the way. At 31 minutes, Michelle went back online to find more useful reference images of double hung windows. After her online search, Michelle thought more about a chemical-based solution to cleaning the window tracks and decided that the user doesn't need anything new to do that, they can just use the cleaner they already own. At 34 minutes, Michelle asked herself "why do I need to make this?", and she revisited the problem statement. At this point, she seemed struggle with how to move forwards; she didn't think a robot could be easily built to automatically clean the window tracks, and she was starting to think spraying chemicals everywhere was not desirable and may not even be effective (section e in Figure 56).

At 36-minutes, Michelle realized that if household cleaner couldn't unstick the window, the user would still need a device to help open the stuck window, and so she began thinking of a third concept that used vibration to loosen the stuck window. Michelle envisioned a rotating electric motor that was transformed into a repeated up and down motion through some sort of mechanism. She couldn't think of a mechanism right away, and so went to the internet to find a mechanism that would translate rotational motion to linear motion. She quickly came across a piston as well as a scotch yoke mechanism that Michelle remembered designing in SolidWorks in ME 100. After finding some useful mechanisms, Michelle started thinking about the power supply and debated using either batteries or plugging in to an electrical outlet. She wasn't sure how much power her device would use, so she went online to try and find the power a small electric motor would use. Ultimately, she avoided making a decision on the power supply and went back to the design of her mechanical device. The next structure Michelle worked on was how her vibrating device would attach to the window. She wanted the device to be able to push up, and pull down on the window, so she recognized she would need a mechanical connection to the window so that her device could operate in both directions. Michelle thought of some options for connecting her device to the window, before stepping back to see if her solution met the initial requirements she set out for the device (section f in Figure 56).

Near the 44-minute mark, Michelle revisited her requirements from earlier in the design activity to make sure her solution met the problem. Michelle thought her device mostly met the requirements (though she had forgotten about the stability of the device). During this verification, she made some changes to her requirements (e.g. ease of use became ease of use and installation) and she also used this time to rank her criteria to determine which were most important – Michelle felt the weight of the device was more important than the materials it would use or the cost. At 46-minutes, Michelle paused to try and think of other solutions to the problem, and then showed the interviewer the sketch of her device, which was very quickly done with little detail. Michelle went online to see if there are any existing devices that solve this problem and was not able to find anything useful, and so went back to thinking through her third concept. At 48 minutes, Michelle began thinking about the safety and stability of her device when in operation. She decided to rely on a windowsill to provide the stability to her vibrating device and thought about how some small kitchen appliances clamp on to the kitchen counter as one idea for how to attach her device to the windowsill. With that detail decided, she began sketching the window and her solution in more detail. Michelle thought about clips to attach to the window, but decided suction cups might be a better option. Just before 55 minutes, Michelle went online to see if there was a lot of variation in double hung windows that would not work with her device. After a short search, she decided her solution would work with the majority of windows and that she was ok if her device doesn't work on 100% of existing windows (section g in Figure 56).

At 56 minutes, Michelle began thinking about the materials and components she would use in her design. She started with thinking about the specific motor she would use in her design, and she struggled to specify what size or type of motor she would need. In her first attempt to answer this question, she decided to try and specify a maximum force before a wooden frame would be damaged. Michelle went online to find the mechanical properties of wood and quickly gave up as she didn't understand the values she was reading. Michelle ended up specifying a desired force of 20 N: "I'm gonna make a guess of like: it should generate 20 newtons without knowing what 20 newtons is, so if it's wrong then, Hey, it's wrong." She then attempted to understand what that force meant for the specifications of her motor. Michelle briefly looked online for help in solving this issue, but quickly gave up on doing the math and just left it as an unknown and moved forward without quantifying the required torque from the motor. Michelle then thought about what materials she would use in each part of her solution; using plastic where possible, but metal for areas like the windowsill clamp and the vibrating arm that attaches to the window. When thinking about how to attach to the window, Michelle went through a couple options including adhesive and suction cups, with suction cups being her preference as they can more easily be removed and reused. While thinking of materials, Michelle thought about using carbon fibre instead of metal, commenting that she would need help from an expert to determine if both options would be strong enough to be used without deforming. Michelle then brought back her criteria, relating material choice to overall mass of the machine, and cost; Michelle prioritized strength, and then mass, and finally cost as the criteria to decide between the two materials (though she didn't actually do this comparison). Just before the 70-minute mark, Michelle thought about the overall mass of her device now that she had thought of most of the materials she would need and felt that she had met her target of being under 10 kg (section h in Figure 56).

Just past the 70-minute mark, Michelle began thinking about how she would test her prototype. This section was not coded as it was not an actual evaluation of her solution, but what she would like to do once the prototype was constructed. After a minute or two of that, Michelle remembered that she had not specified the power supply for her device. She didn't think that a battery powered device would be strong enough, but she liked the idea of having the option of being either battery powered or plugged in to an electrical outlet. Michelle confessed that she was not able to specify these details but did think about some of the other features it would need (e.g. an on/off button). Michelle also thought about some sensors she would like her device to have to help ensure it was being used safely. These included sensors to detect whether it was plugged in to an outlet, or on battery power; a sensor to detect the force the motor was applying to the window and shutting off before it damaged anything, and a tilt sensor to detect if it was installed correctly to the window. With these last details written down, Michelle declared she was finished (section i in Figure 56). Though not shown on the timeline, after completing the design, Michelle summarized what she had written/drawn on her tablet at the interviewer's request.

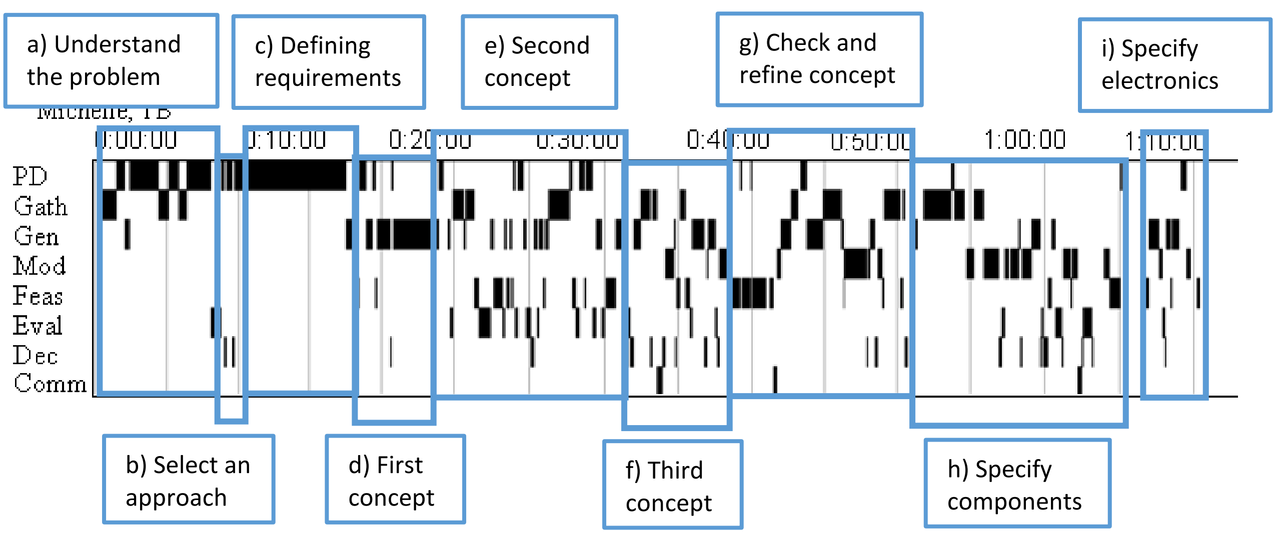


Figure 56 Overview of design process, 1B interview with Michelle

Jill

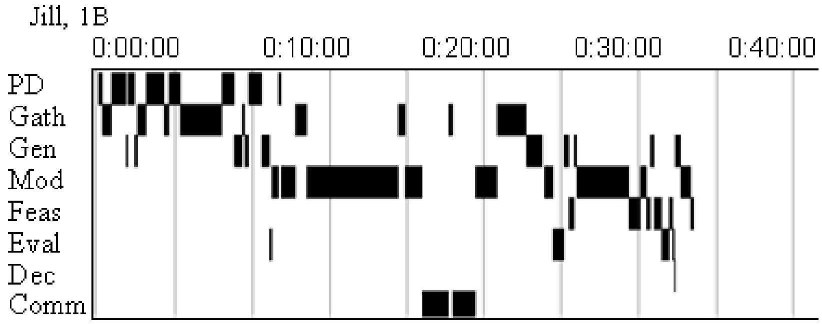


Figure 57 Design timeline of 1B interview with Jill

After an initial read of the problem statement, Jill went online to find out what a double hung window was and then sketched the window to have a starting point to work off of. Jill then started thinking about where the window would stick, with some initial ideas to address those issues. For example, there could be debris in the slides that are causing the window to bind, where lubrication could help. Just before 3 minutes, Jill clarified with the interviewer if these windows slid up and down, or tilted, and was told that the vertical sliding motion was the main way that a user would operate this style of window. Jill then wrote out a summary of the desired motion in the window (i.e. up and down) with possible places where obstructions could occur. At 4.5 minutes, Jill took another look at the windows online and then kept adding to her written definition of the problem. At 5.5 minutes, Jill went online to look at the operation of the window in more detail including how the various window sash components are assembled. After her online search, Jill defined the problem as a stuck window that required extra force to open (section a in Figure 58).

Starting at approximately 8.5 minutes, Jill began thinking about ways to apply an external force to the window to get it moving again. She also though about an initial step of cleaning out any debris in the slides using pressurized air before trying to force the window open. For this part of the solution, Jill formulated a goal of reducing the force the user would have to apply to the window, while maximizing the force on the window to get it open. She also thought of other goals, like the solution needs to be cost effective (without further defining what that meant). At approximately 11 minutes, Jill began thinking of ways of amplifying the force of the user on the window. This included ideas like pulleys and gears, and could be motorized, or hand powered. Jill did a quick assessment that a motorized solution would be more accessible and so she started to pursue a motorized solution in more detail. Near the 13-minute mark, Jill went back online to research how double hung windows get stuck in the first place. This search seemed to confirm her idea that it was largely dust and dirt in the slides and that cleaning and/or lubricant could help. As she continued designing her solution, other ideas would come up, like the possibility of vibrating the window to help shake it loose. Her initial design focus seemed to be on the elements that the user would interact with, like the buttons, as well as the placement of the large components like the motor, though as she moved into modelling, Jill started to get very quiet and difficult to understand, speaking very softly, and mostly to herself. As Jill designed, she would do a mix of sketching, and of writing out text (section b in Figure 58).

Around the 17-minute mark, Jill paused, seemed to make a decision, and then began sketching what would end up being her final solution to the problem. During this time, she continued to work on the same concept, making incremental progress as time went on. This solution was a winch mounted above the window with hooks on the end of a cable that connected to the window handles. Just before the 20-minute mark, Jill walked over to inspect the window in her room. She commented that she did not have the same style of window, but once she returned, she continued her sketching. During the next minute or so, Jill added compressed air and lubrication systems to her winch setup, and then at 21 minutes, Jill began writing out the written instructions for how the user would interact with her device, and the order that her device would carry out its various functions (i.e. use compressed air to clean any debris, then drip lubricant, and begin winching). Around 23 minutes, Jill briefly went back online to make sure she had the correct names for the parts of a window, and then she continued writing the instructions. At 24 minutes, Jill began working on her sketch again; adding compressed air and lubricant nozzles to the other side of the window to clean and lubricate both sides at once (section c in Figure 58).

At 26 minutes, Jill went back online to watch videos of double hung windows being used. Near the 28-minute mark, Jill began thinking about how her device would pull down the window. After initially struggling to think of a way to have her device both open and close the window, she eventually identified a way to have her device work in both directions (section d in Figure 58). Starting just after the 30-minute mark, Jill began thinking of a way to extend her device so that it could move both window sashes in a double hung window. She started by addressing how to hide her mechanism from view to improve the aesthetics of the installed device, before moving on to the necessary additions to her device that would help move the second window sash. Jill’s device uses the same motor to move both window sashes simultaneously, and around 32 minutes, Jill realized the device could run into issues if only one of the window sashes is stuck, while the other is free to move. As with many of the previous issues she identified in her design, Jill didn’t pause to evaluate the severity of the issue, or think of potential solutions, she just modified her description of the device's operation, and made small mechanical changes to lessen the issue (section e in Figure 58).

With the operation of the second sash decided, just before the 35-minute mark, Jill paused and assessed her design's functionality by working through the order of operations of her device. During this assessment, she realized she had forgotten about her intention to add a vibrating element to her solution, and immediately selected a scotch yoke mechanism for that function. This mechanism was included in an EGAD lecture in her 1A term, and so was quickly recalled by Jill. She continued to assess the functionality of her device, including how the user would refill the compressed air and lubricant. She briefly thought about adding a brush to her device to clear any debris that the compressed air didn't get, but she felt the user could do that manually if required. After taking one last look at her solution, Jill declared she was finished (section f in Figure 58).

Analysis

Jill spent 38 minutes and 40 seconds completing the 1B design activity, 7 minutes less than the average time (see Figure 58). In that time, she transitioned between design steps 48 times, at an average rate of 1.24 transitions per minute, under the average of 1.52/minute. This is virtually the same length of time as Jill spent in 1A where she spent 37 minutes and 15 seconds, however her transition rate was faster in 1B (1.24 vs. 1.1).

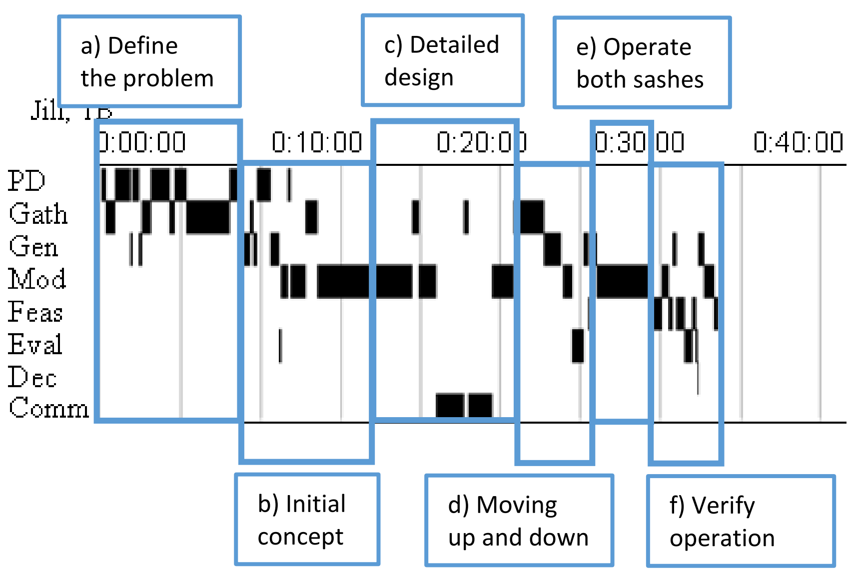


Figure 58 Overview of design process, 1B interview with Jill

Table 67 shows the percentage of time Jill spent in each phase of the design process. Jill spent more time gathering information and less time generating ideas in 1B than in 1A, but generally she was consistent with where she spent her design time. The majority of Jill's time was spent in problem definition, gathering information, and in modelling (these 3 represented nearly 75% of her total design time). As with the 1A interviews, Jill spent a larger percentage of her time in modeling than any of the other participants by a wide margin.

Table 67 Percent of time spent in each design step during 1B interviews, Jill highlighted

Design Phase	Michelle 1B	**Jill 1A**	**Jill 1B**	Patrick 1B	Chris 1B	Jay 1B	Oscar 1B	MJ 1B
Problem Definition	23%	**15%**	**14%**	32%	23%	19%	14%	29%
Gather Information	17%	**12%**	**20%**	19%	22%	21%	21%	8%
Generate Ideas	20%	**14%**	**9%**	27%	5%	7%	10%	18%
Model	11%	**38%**	**39%**	8%	17%	21%	29%	18%
Feasibility Analysis	10%	**3%**	**6%**	5%	1%	5%	4%	8%
Evaluation	7%	**5%**	**4%**	3%	1%	2%	3%	2%
Decision	4%	**1%**	**0%**	1%	0%	0%	0.5%	2%
Communication	1%	**10%**	**8%**	4%	23%	18%	12%	10%
Transitions (mean=70)	152	**40**	**48**	113	27	36	45	68

There were several unique qualities to Jill's designing when compared to her peers. Similar to her 1A interview, Jill struggled with speaking out loud while designing, despite repeated prompting from the interviewer. When she did speak, she spoke quietly which made it difficult to decipher the exact details of what she said. Unlike most of her peers, Jill designed a solution that attempted to address the root cause of the issue (by adding devices to clear debris from the slides and add lubrication) while also applying a force to get the window sash moving again. Jill did not seem to employ the procedural knowledge of design taught in ME 100; Jill wrote goals for her solution, however, she didn't seem to use the language taught in either ME 100 (i.e. defining criteria and constraints) or ME 101 (i.e. defining functional and non-functional requirements) when doing so. Jill also did not do much sketching, instead describing her design ideas mostly with written text. Jill also spent a significant portion of her time researching windows, their operation, and how they can get stuck; most of her peers did limited searching on the root cause of a window sticking, but this was an important concern that Jill wanted to address with her solution. Jill did only limited reflection on her original design goals as the process went on, however she evaluated the operation of her device at multiple points during the design process, which resulted in changes to her design. For example, the second operable window sash was not part of her thinking until after more than 30 minutes into the design activity, however once she realized that it should also operate, she altered her design to accommodate the new function. As with Michelle, there were few explicit uses of the factual or conceptual knowledge taught since arriving at university except for the scotch yoke mechanism taught in EGAD.

The last detail worth discussing is that Jill's presentation of her solution runs for 9 minutes at the end of the design activity. This communication was not included in the timeline because it is more an explanation of everything she did during the activity, as opposed to continued work on the problem. She did so little talking while she was designing that it then took her 10 minutes at the end to explain her design. Ultimately her final design was not fully developed and was more conceptual in nature. It was missing most of the details that would be required to build it, especially in the electromechanical elements of the design which were described only superficially.

Reflecting on the behaviours of a beginning designer described by Crismond and Adams, Jill showed a mix of beginning design traits, and traits of a more experienced designer:

- Similar to 1A, Jill spent time understanding the requirements for the device, writing out goals for her solution, and Jill evaluated her solution and identified additional functionality at several points in the process,
- Similar to 1A, Jill researched the problem space including the operation and construction of windows and reasons for why they might get stuck, but did not do any searching for design alternatives or existing solutions,
- Unlike in 1A, Jill did very little ideation during her design process, typically only coming up with one option to pursue,
- Unlike in 1A, Jill spent some time thinking about the operation of her device which led to additional functionality and refinements to her solution,
- Similar to 1A, Jill designed a device that was missing a lot of detail, especially in the electro-mechanical aspects of the design,
- Similar to 1A, Jill made decisions with no evaluation, relying on her intuition, and
- Jill developed a single design concept and unlike her 1A interview, Jill included iteration while designing, improving or even adding functionality as she thought about her solution's operation

Patrick

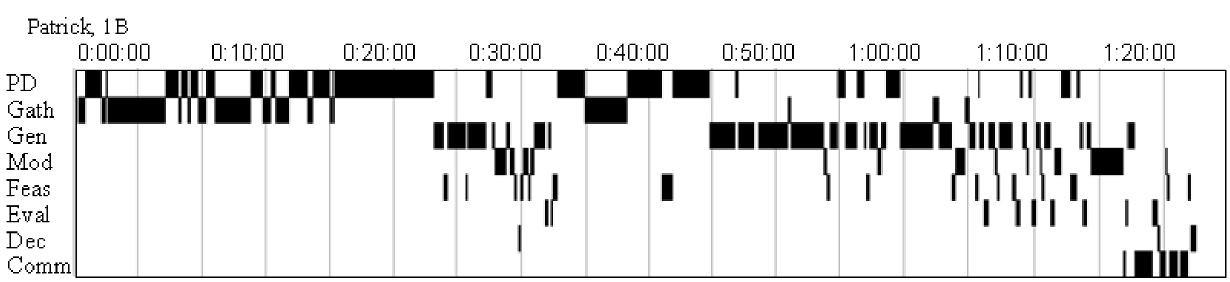


Figure 59 Design timeline of 1B interview with Patrick

Patrick started by searching online to better understand what double hung windows are, and how they operate. Patrick began thinking about where in their operation they get stuck: when closed, when opened, or when the two window sashes slide past each other. Patrick looked at websites which describe their operation, and the suggested maintenance for double hung windows, recognizing that dust/debris in the window slides may be the cause of them sticking. At the 7-minute mark, Patrick wrote down what he saw as the root cause of the problem: dust/dirt getting in the tracks and binding the window. He also began thinking of the locking mechanism and the tilting mechanisms, and realized he needed to better understand how these worked, and so went back online to find a video showing their operation. One of the videos showed a wooden window sash, and Patrick wondered if expansion and contraction in the wood might cause some of the sticking issues. Around 14 minutes, Patrick revisited his summary of the root causes for the problem and ruled out the locking mechanism as a source of the problem. As Patrick went back and forth between his online research and his description of the cause of the sticking problem, he left in the possibility that the tilting mechanism might be the cause, though near the 19-minute mark, he decided the tracks were likely the main cause of any sticking problems (section a in Figure 60).

At 21 minutes, Patrick started sketching different configurations of the stuck window – the window could be fully closed and stuck in the tracks, or the window sashes could both be partially open and stuck on each other. Just before 25 minutes, Patrick redefined his problem as: "How can I prevent the tracks from getting dirty?" Over the next couple minutes, he wrote down a list of the types of dust and debris he might have to contend with including things like leaves and sand from outside, to dust, dirt, and hair from inside (section b in Figure 60). Starting around 28 minutes, Patrick started thinking about ways to keep dust and debris out of the tracks (or to clean it out automatically as the window is used). He mentioned ideas like brushes which would sweep dust out of the tracks as the window slid, similar to ones present on industrial machines like milling machines and bandsaws, and a modified window frame where the dirt could fall through the sides of the frame instead of getting caught in the tracks. Patrick spent some time around 34 minutes thinking through the implications of his modified window frame on the strength of the overall window assembly, and decided he can't modify the window frame too much or he risks weakening the overall assembly. At 36 minutes, Patrick wrote down some of the open questions he would need to resolve with this design including the size of the holes in the frame to let dirt go through, and the shape of the holes. At 38 minutes, Patrick spent time thinking about where this dirt would go, and realized he didn't know how much dirt he could expect. At 40 minutes, he began to search online for the lifespan of a window to try and understand the scope of the problem, deciding 8-20 years was reasonable, but that he should plan for 40 years worth of use before windows are replaced (section c in Figure 60).

At 48 minutes, Patrick revisited the original problem statement, and decided to pursue an alternative solution path; to design a device that can help a user apply more force to open a stuck window. Beginning at 50 minutes, Patrick started to generate ideas for how to operate the window by thinking through the force (direction and location) he would exert on the window to open it including an upwards force on the lower sash, a downwards force on the upper sash, and a force on both that would squeeze them together to try and move both at once. At the 55-minute mark, Patrick seemed to reduce his options to a "spreading apart force" or a "push together force", acting on both sashes at once to try and get them unstuck. After summarizing the types of force his device could apply, Patrick began thinking of how the user and/or the device would interact with the window; beginning with thinking about different options for the handle on the window. Patrick's first concept for his device was a wedge that could apply an upwards force on the underside of the handle of the lower sash. His second concept was a small linear acuator that could be electric, or could be a pneumatic cylinder operated by pumping something like a tire pump. Patrick thought about some of the shortcomings of this small linear actuator, and then at the 1-hour mark, he revisited the problem statement to try and understand what physical ability he could assume the user has. At 61 minutes, he began thinking of other concepts for opening the lower sash. His next concept was a lever (viz. a crowbar) to pry up the stuck window, which might require a bigger and/or stronger handle to be able to operate. Just before 65 minutes, Patrick stated a constraint (though he didn't use that language) that his device must be able to be operated by someone who may not have full use of both of their hands/arms. After reading the question again, at 65 minutes, Patrick seems to realize that his focus needs to be on an external device to open the window, not the internal changes that he started the activity with (section d in Figure 60).

At 66 minutes, Patrick spent some time thinking of possible solutions for a window that was stuck when tilted. Patrick tried to think of some different ways for a user to push a tilted window back into the frame, including how a person could do that from a seated position (e.g. in a wheelchair). After struggling to think of a way to close a stuck, tilted window, Patrick went back to his two earlier ideas for how to apply vertical force to the window sashes. Thinking through the operation of his devices, and how they apply force to the window sash, Patrick questioned whether his device could apply enough force to break the glass. Patrick continued to think about where to apply more force to the window and at 70 minutes went back online to seek more information on the upper window sash and whether it typically has a handle. For the next couple minutes, Patrick summarized his various solutions for different parts of the problem and assessed which situations they would be best suited to solve; for example, a wedge for a stuck window that is closed, a bar with a hook for a window stuck tilted outwards section e in Figure 60).

Near the 72-minute mark, Patrick started thinking about combining his different ideas into one solution. He though about a modified crowbar that could extend its length when needed, but also brought up his wedge and his linear actuator ideas from earlier. At 76 minutes, Patrick revisited the problem statement, and did quick evaluations of his earlier solution for keeping the dirt out as compared to his new ideas of applying force to get the stuck window open. At 77 minutes, Patrick revisited the problem, mentioning the term criteria for the first time as he discussed minimizing the amount of force the user would need to apply to his device to open the window. Patrick also thought about the impact of applying extra force to the handle on the window sash, recognizing that part of his solution may need to be a reinforced handle of some kind. At 78 minutes, Patrick seemed to fully discard his earlier problem frame of avoiding the window getting stuck in the first place, opting to address the problem that the window is currently stuck closed, how can we open it (section f in Figure 60).

At 79 minutes, Patrick started to refine his crowbar concept so that it could work when the window is fully closed, or partially open by adding a removable/replaceable extension so that it could reach the bottom of the window if it were stuck partially open. At 80 minutes Patrick began sketching this crowbar-like device, and then the interviewer warned him that there were only 10 minutes left in the design activity. Patrick began sketching different forms for his crowbar/lever device before stopping himself from reinventing the wheel, ultimately just selecting the shape of a traditional crowbar. At 82 minutes, Patrick began thinking of the material he would use for his solution, intentionally trying to avoid using metal to avoid damaging the window. Patrick then pivoted to designing the extension to his crowbar that could work with a partially open window. Patrick thought about how it would connect to the crowbar so it didn’t fall off when in use, and thought about the end of the extension that interfaces with the window sash and how to spread out the force it’s applying to avoid damaging the window. Patrick ended his design session by summarizing the design of his crowbar solution and extension bar, and how it would be used to open the bottom window sash. During this summary, Patrick realized his solution was not built to help with a stuck upper sash, but he was quickly running out of time and so he made the decision to just focus on the lower sash (section g in Figure 60).

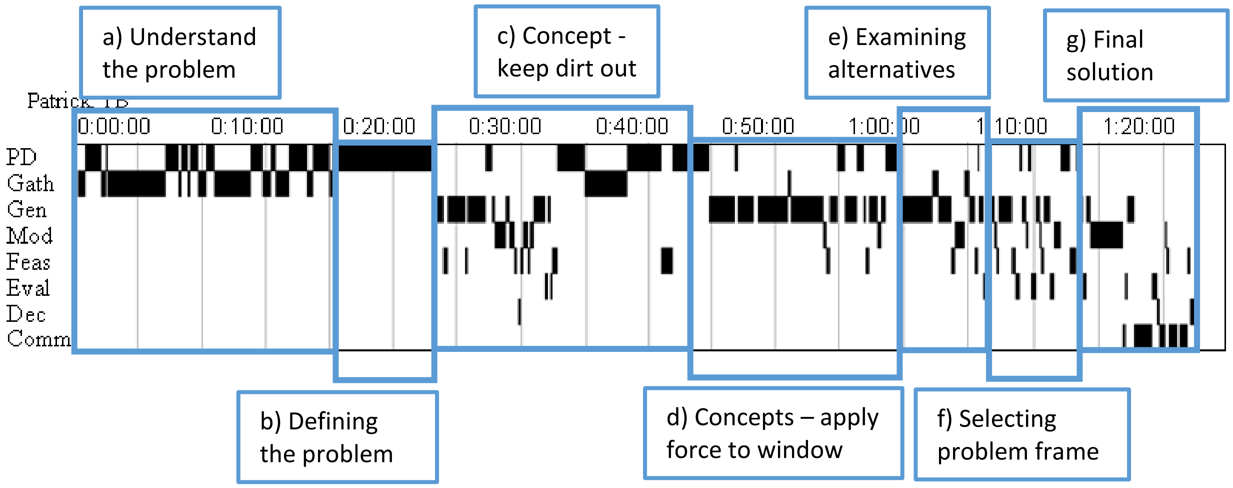


Figure 60 Overview of design process, 1B interview with Patrick

Jay

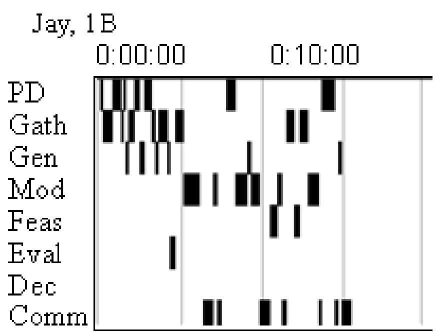


Figure 61 Design timeline of 1B interview with Jay

Jay started by gathering more information on double hung windows. He first searched online to find out what a double hung window is, as he was not familiar with how they operated, and after a very brief look online, he asked the interviewer some more detailed questions about their operation (e.g. can the upper window sash slide as well?). One he found out that the upper window sash can also move in a double hung window, Jay deliberately chose to ignore the upper sash and treat it as fixed (section a in Figure 62), effectively simplifying the problem to a single-hung window. Jay then thought about what could cause this type of window to stick (i.e. debris in the window track) and thought of a first design concept: an arm that would force the window open. With this partial solution in mind, Jay asked the interviewer more questions about how these types of windows operate; in particular he was wondering if the two window sashes can also tilt out of the frame. While it could not be confirmed, it seems that Jay left his internet search open on his screen throughout this time. At this point, Jay again chose to simplify the problem and ignore the tilting operation that modern double-hung windows are capable of, focusing his efforts on the vertical sliding of the lower window sash. Jay then began thinking of his solution in more detail, deciding at the 3-minute mark that he wanted to avoid any electronics in his solution to avoid complexity, and any risk of electrical devices near areas with potential to get wet (section b in Figure 64).

At the 4-minute mark, Jay began searching for a mechanism that could apply a force to the window. As he thought about this, he began refining his idea of the user of the device. Jay wanted his device to be capable of being used from a seated position and so thought that the user applying a downward motion would be the best option. At this stage, Jay acted out the motion of the user, testing that a downward pulling motion would work, and then began looking online for mechanisms that could translate a downward pulling motion into upwards motion on the window (section c in Figure 64).

Jay quickly found a mechanism (viz. a reverse motion linkage) that he felt would work and began sketching his solution. At this stage, the solution largely consisted of the linkage itself with a location for a handle for the user. With his initial mechanism sketched out, at the 8-minute mark Jay began describing the testing he would like to complete once he had built a prototype of the mechanism (section d in Figure 64). At this stage, Jay is wanting to evaluate the forces on each side of his mechanism: how hard can the user pull down? How much force is required to open a stuck window?. Jay, however, did not actually try and evaluate these questions analytically.

With an initial concept in mind, Jay began thinking about whether his device would be used temporarily or installed permanently on the window. Jay again thought about the needs of a disabled user and decided it might be challenging for a disabled user to setup and operate a temporary solution. Jay then continued to sketch the solution now that he decided it should be permanently installed on the window (section e in Figure 64). Near the 11-minute mark, Jay started thinking about materials for his solution; realizing that it probably needs to be metal due to the expected forces involved in opening a stuck window. Jay then began to think about the feasibility of his solution, and what the force of his mechanism would do to the lower window sash. Jay was concerned if the force was only applied to one side of the window, that the sash could twist and bind in the frame, and so he added a mechanical connection to the far side of the window as well so that the force was applied more or less equally to both sides of the window sash (section f in Figure 64).

At the 12-minute mark, with his initial concept more or less complete, Jay began asking more questions about how the upper window sash operates. With a better understanding of how the window operates, Jay began to assess how his device would work on a double-hung window (as opposed to the simpler single-hung window that he had selected early on). After 3 rounds of questions with the interviewer, Jay became concerned with the safety of the movable upper sash. Jay did not understand why a user would want to open the upper sash, and so decided he would add a latch so that it couldn't be moved freely (section g in Figure 64). Jay ended his design time by describing the final solution and how it would be installed on the wall, as well as the user testing he would want to do with his prototype (e.g. can it be operated single-handedly, etc.).

Analysis

Jay completed the 1B design activity in 16 minutes, the shortest time taken by anyone in either interview, and 20% shorter than the 20 minutes he spent on the design activity in 1A (see Figure 62). In 1B, he transitioned between design steps 36 times, at an above average rate of 1.8 transitions/minute; though this was a much slower rate than the 3.2 transitions/minute he averaged in 1A.

Table 68 shows the percentage of time Jay spent in each phase of the design process. In 1B, Jay spent more time in problem definition, gathering information, and communication, and less time in every other phase of the design process compared to 1A. The differences are especially pronounced when considering his total design time was only 16 minutes in 1B (20% shorter than in 1A). Jay spent the majority of his time in problem definition, gathering information, and in modelling (together representing 61% of his design time).

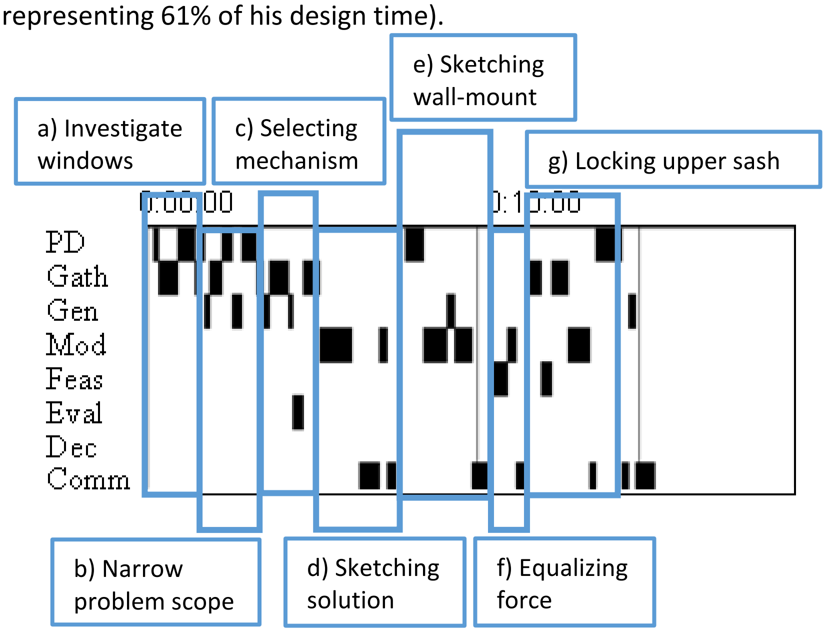


Figure 62 Overview of design process, 1B interview with Jay

Table 68 Percent of time spent in each design step during 1B interviews, Jay highlighted

Design Phase	Michelle 1B	Jill 1B	Patrick 1B	Chris 1B	**Jay 1A**	**Jay 1B**	Oscar 1B	MJ 1B
Problem Definition	23%	14%	32%	23%	**9%**	**19%**	14%	29%
Gather Information	17%	20%	19%	22%	**17%**	**21%**	21%	8%
Generate Ideas	20%	9%	27%	5%	**12%**	**7%**	10%	18%
Model	11%	39%	8%	17%	**26%**	**21%**	29%	18%
Feasibility Analysis	10%	6%	5%	1%	**16%**	**5%**	4%	8%
Evaluation	7%	4%	3%	1%	**10%**	**2%**	3%	2%
Decision	4%	0%	1%	0%	**2%**	**0%**	0.5%	2%
Communication	1%	8%	4%	23%	**8%**	**18%**	12%	10%
Transitions (mean=70)	152	48	113	27	**64**	**36**	45	68

Jay clearly made decisions during the design activity - he selected the linkage and the location for the handle, for example – however, he never articulated his decision-making and never considered more than one option. One of the most important decisions he made was likely the choice of linkage in his final solution; a quick online search for "linkage" turns up the mechanism he selected as one of the top results. Given the speed at which he selected it, even if other mechanisms were on screen, he never considered them, instead choosing the first plausible option he came across.

Jay knew the evaluations he wanted to complete, but in the past, he has relied on a built prototype to conduct these evaluations, and so he was not able to complete an evaluation here. As one example, a quick calculation of the forces involved on each side of the mechanism was well within his capabilities after taking first year physics, and yet he didn't even attempt it. Jay even seemed to ignore simple geometric evaluations; his drawing was never completed at scale in comparison to the window, and so shortcomings of the solution as it scaled up to full size were never identified (in his sketch, the mechanism was as big as the entire lower pane of the window). It is interesting to note that Jay's winter work term role was in testing and validation, and yet he conducted almost no evaluation or decision-making in his design process.

Jay's design was missing the details required to manufacture his device. This included both relatively simple things like the shape of the handle, and more complex things like what material(s) the parts are made of, their actual shape, or how they attach to each other. Jay thought very briefly about how this would attach to the wall, but never gave any thought to how it would attach to the window itself. Overall, Jay did not seem to leverage the knowledge he was taught in either his 1A term or in his work term.

Reflecting on the behaviours of a beginning designer described by Crismond and Adams, Jay showed virtually identical behaviours as in his 1A interview, he:

- spent some time understanding the requirements for the device, but did little to no iteration on the problem definition as the solution proceeded,
- conducted some research into the operation of this style of window, but did not conduct a broad search for design ideas, and fixated on the first useful mechanism he found in his search
- conducted no tests of his proposed design, though he did articulate the tests he would like to do once he had built a prototype
- designed a device that would be challenging to both install and operate for a disabled user,
- made decisions without weighing any options, and
- included no iteration or reflection during the process

Oscar

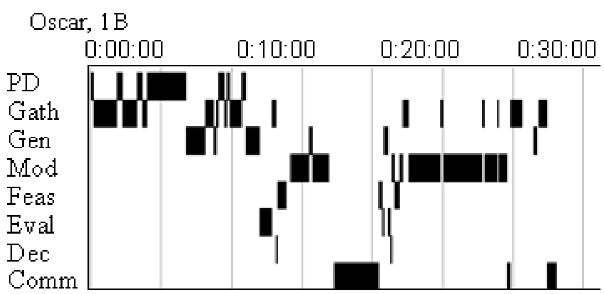


Figure 63 Design timeline of 1B interview with Oscar

After briefly writing down the problem statement, Oscar jumped online to research what double hung windows are. He spent a couple minutes looking at the windows online, including some research into how they can get stuck. Oscar defined the problem as having dirt/debris in the rails that are stopping the window sashes from sliding, as opposed to obvious adhesives like caulking or paint. At the 3-minute mark, his investigation shifted to how you could unstick this style of window, and where you could attach something to, or where you could apply force to open the window. After briefly thinking about this, Oscar decided that his solution should be able to assist in opening both the upper and lower window sashes, not just the lower one (section a in Figure 64). With an initial problem scope, and a basic understanding of a double hung window, Oscar spent some time writing constraints and criteria for his solution. His constraints included some arbitrary concerns like it should cost less than $100, as well as constraints like it should fit any size of window, can be operated by a user with limited mobility, and can open both the upper and lower window sash (section b in Figure 64).

At the 7-minute mark, Oscar began thinking of potential solutions to the problem. These included big picture concepts like screws, levers, gears, hydraulics, impacts, etc. Around 8 minutes, Oscar went back online to look at windows in more detail to see how a device could interact with it. This ideation led to the generation of additional constraints for his solution. Oscar also made the assumption that he could ignore the tilting operation of some double hung windows, he was only working with stuck sliders. At around the 11-minute mark, Oscar began thinking of potential solutions in more detail; thinking not just of general concepts like before, but of ideas and how they would interact with the window itself. Though he hadn't selected them yet, it was during this ideation that Oscar identified the two ideas that he would ultimately pursue: a crowbar, and a hydraulic car jack (section c in Figure 64). With some solution concepts identified, Oscar began thinking of the pros and cons of each type of solution. He was mainly thinking about how his device would interact with the window when it was both fully closed, and also when it was partially open. Oscar quickly decided that the crowbar was a good solution to pursue because of its ease of storage and use (section d in Figure 64).

Starting at approximately the 14-minute mark, Oscar started sketching his crowbar solution. During this time, he seemed to struggle vocalizing his thoughts, frequently going silent while he sketched. At around 16 minutes, he spoke briefly about ideas for the shape of the tip of the crowbar and how his idea would be able to get under the fully closed window to start prying it open. With that detail decided, Oscar largely went silent again as he continued to sketch the crowbar. At approximately 18 minutes, Oscar decided he wasn't satisfied with his sketch of the crowbar, and so he redrew the solution. Throughout this stretch of time, Oscar spoke very little despite being reminded to keep talking. Just before the 21-minute mark, Oscar presented his crowbar solution to the interviewer (section e in Figure 64). At the end of the brief presentation, Oscar realized the crowbar would not be effective if the window was stuck partly open, and that he would need another solution. He decided to sketch a hydraulic solution, because he thought it would be interesting to design one. After briefly sketching, he realized that his prior solution and this one might be complementary, that having both could be beneficial as his first solution works well for a fully closed window, and a car jack based device could work for one that is partially open (section f in Figure 64).

At the 23-minute mark, Oscar searched online for a car jack to see how they operate before going back to sketching his car jack solution for a partially open window. Like his early time sketching, Oscar did not vocalize many thoughts while he was sketching. He would occasionally mention concepts like a 4-bar linkage but focussed primarily on his drawing. While sketching, he occasionally would reference his online browser where he had pictures of car jacks open. At the 30-minute mark, Oscar presented his solution to the interviewer (section g in Figure 64). After presenting his solution, Oscar went back online to look at the windows again to see if there were any other things that came to mind. At this point, Oscar felt he had run out of what he could do with pen and paper, and expressed a desire to build a prototype of this solutions to see how they would operate. In this final phase, Oscar seemed concerned that he had finished too quickly, perhaps in response to the interview. Oscar seemed concerned at a couple points in the interview with producing good quality data for the research being conducted. After being reassured by the interviewer that he could stop whenever he was satisfied with his solution, Oscar declared he was done. He ended with a brief presentation of his two solutions at the interviewer's request (section h in Figure 64).

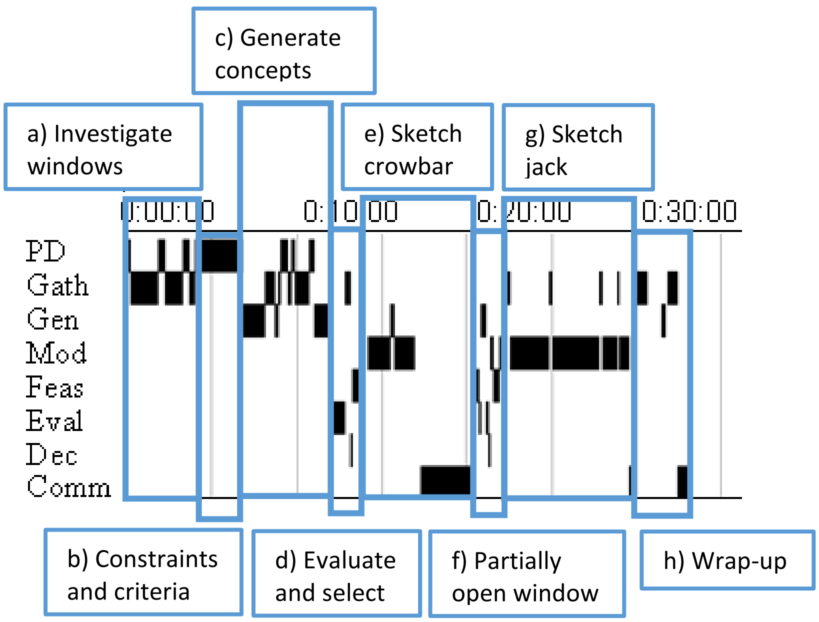


Figure 64 Overview of design process, 1B interview with Oscar

MJ

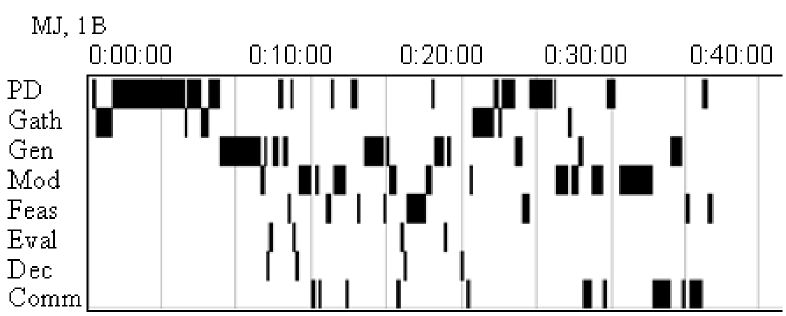


Figure 65 Design timeline of 1B interview with MJ

As with most of the other participants, MJ began by researching what a double hung window was, and how it operates. After looking briefly online at the windows, MJ began to think about what was meant by a “disabled user”; choosing to focus on people with physical disabilities like limited vision, limited or no use of hands, etc. At the 3-minute mark, MJ began thinking about what his solution would need to solve the problem. He initially mentioned constraints and criteria, but he instead began using the language from ME 101 and started thinking of functional requirements for the solution. From his spoken comments, MJ seemed to be focussing on functional requirements of the window itself, and not on a device that would interact with the window, however some of his other functional requirements were generic concerns like “easy to use”, and “looks good”. Near the 5-minute mark, he began referring to “constraint requirements”, seemingly a blending of the processes taught in his first 2 design courses. At 6.5 minutes in, MJ was looking a little confused and went back online to research the windows further. At this point, the interviewer intervened and clarified that the problem was to help a user operate a double hung window that was stuck; MJ seemed to be somewhat confused about what the problem was asking. As soon as this was clarified, MJ seemed much more confident about what he was doing, and he immediately framed the problem as needing a device that can open a window that is stuck closed (section a in Figure 66). With his clearer understanding of the problem, MJ adjusted his functional requirement and went online to better understand how a double hung window operates. MJ ended up with one functional requirement for his solution: “to get the window up” (section b in Figure 66), with his non-functional requirements more or less unchanged from the start.

With his problem frame understood, MJ began thinking of as many ways to open a closed window as he could. In this phase of ideation, he was focussed on the mechanism that would apply a force to the window, listing ideas that push from the bottom like a prybar, or a jack, as well as ones that pull from the top like a block and tackle. At the 12-minute mark, MJ decided he liked the idea of a suction cup to attach to the window, and a vertical screw to apply the force. With the initial components of his concept selected, MJ began thinking about how the user would interact with this device. For example, it could be electric and work at the press of a button. MJ thought about a few different systems the user could interact with including pulling a rope, or turning a crank; and as he listed ideas, he would comment on the ease of operation of that system for a disabled user(section c in Figure 66). MJ decided a crank was easy enough to operate, and near the 15-minute mark, MJ transitioned to sketching a first concept.

MJ produced a very simple sketch of a vertical screw that would extend up from the windowsill and attach to a suction cup on the glass of the window and presented that to the interviewer. After showing the initial sketch of the screw and suction cup, MJ added a crank at the bottom that the user would turn to operate the device. MJ briefly commented on the ease of use of his device, and decided he wanted to try and think of a different mechanism that could solve the problem (section d in Figure 66). For MJ's second concept, he wanted to sketch a pulley design that pulled the window from the top. He had some reservations that it would be challenging for a disabled user to install, however he decided it was worth completing a quick sketch to think through the idea more fully. This solution had pulleys above the window with a rope for the user to pull to operate the window. A weight could also be added to boost the user's force on the window. Around 17 minutes, MJ presented this second concept to the interviewer and discussed its operation by the user. MJ then went back to the problem statement to verify that his solutions would be capable of solving the problem. At 18 minutes, MJ decided he wanted to try and come up with a 3rd concept, and he gave himself permission to be more creative with this one. MJ described the third concept like a nail gun that could add a post to the window that the user to grab hold of to open the window. Thinking about this new solution, MJ realized that it would be challenging to supplement the force provided by the user with this solution. Nonetheless, MJ sketched out this solution where the new post would attach to the window frame – compared to his suction cup that attached to the glass of the window itself (section e in Figure 66). With 3 roughly defined concepts, MJ commented that he liked the first idea the best, but he wanted to think about potential downsides. MJ listed a couple perceived issues with the design: he was concerned with the holding strength of the suction cup, he was concerned with the feasibility of the screw mechanism given his lack of knowledge of similar existing devices, and he wasn't sure how it would work in the absence of a windowsill. MJ saw these issues as problems to overcome in his design, and so he wanted to design his first concept in more detail. At 23 minutes, MJ began coming up with solutions for how the device would stand up on the window; for example, it could be free-standing, attach to the wall, or be handheld. MJ thought about this briefly, and then felt that he had stopped making forward progress and so committed to the design so he could move forwards. Just before the 25-minute mark, MJ expressed a desire to speak with others about the design to "see what they think", but in the absence of that possibility, he persists in thinking through the feasibility of his design. MJ presented the initial sketch of the idea to the interviewer before going back to his sketch to think about the suction cup in detail (section f in Figure 66).

Just before 26 minutes, MJ began searching online for more information on the industrial suction cups that professionals use to move large panes of glass. MJ wasn't sure how the strength of these suction cups were specified, but he found one that had a lifting capacity of 200 pounds. With this information, MJ updated his problem constraints for both how much force his solution would need to exert, as well as a maximum weight of his device for the user to be able to move it around and install it. MJ was concerned about the overall weight of his solution and so gave some thought to the materials he would select; commenting as he did so about his materials course that he was enrolled in at the time. MJ continued to think about constraints for his solution including a maximum cost of $20 to manufacture, and that his device should also help the user to close the window as well as open it (section g in Figure 66). With his updated and expanded project constraints, at approximately 33 minutes MJ began sketching the solution in more detail. After sketching a suction cup he saw online, MJ began designing the interface between his vertical screw and the suction cup itself, stopping occasionally to present his design to the interviewer. Near the 35-minute mark, MJ realized he hadn't specified the maximum range of motion his device should have, so he revisited his constraints and decided it should lift up to 18 inches. MJ then began sketching the vertical screw in more detail; though he was not able to describe the internal mechanisms needed to translate the motion of the hand crank into vertical movement of the screw (section h in Figure 66).

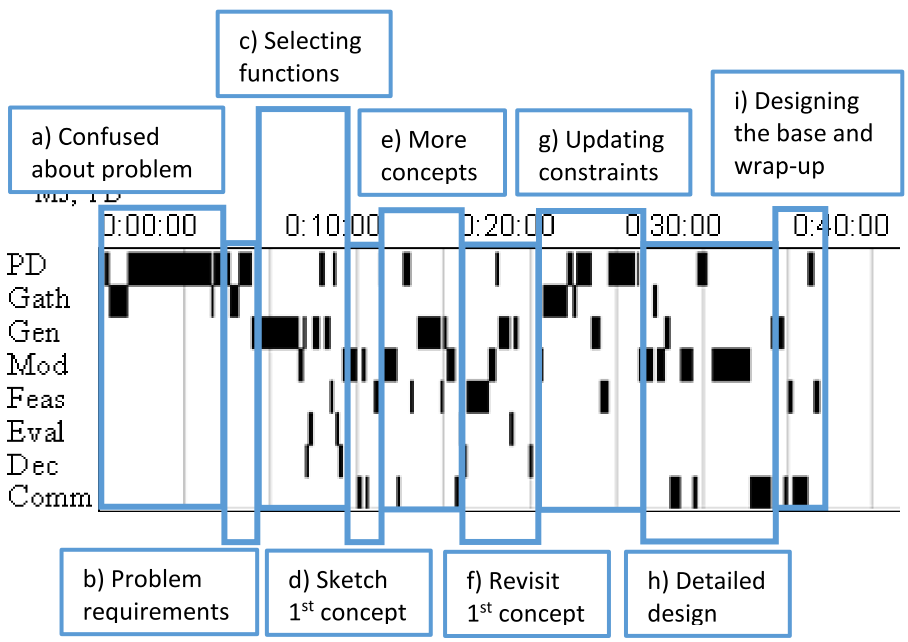


Figure 66 Overview of design process, 1B interview with MJ

The last detail MJ designed was the base for under the vertical screw. His primary concern was the depth of the base in relation to the window and suction cup, and so he left his design as two parts so the user could position them in line with each other manually. MJ described the order of operations to install and operate the device and then described the necessary user abilities to use the design (viz. the use of at least one hand and the visual acuity necessary to line up the parts on the window). MJ ended the session with a brief assessment that his device was user friendly (section i in Figure 66).

Appendix G Detailed Data – 1A Personal Epistemological Development

Jay

Jay took a computer technology course in high school where he learned about computers, electric circuits, and was given a chance to experiment with CAD and 3D printing. These are all useful domains to engineering, however when asked about the projects in the course, Jay said they were just "following the steps" given to them by the longstanding teacher, and that there was little or no room for creativity in the process. The lack of openness in the course would limit the possibility for epistemic doubt in the students, however Jay might have still benefited from reciprocal causation by seeing what his peers came up with. The presence of resolution strategies, like reflections, or social interactions was not clear from the interview.

Jay only developed a single concept during his design activity; however, he completed an iteration on the design, transitioning from a portable, handheld device to one that mounts to a counter or table for better stability. Jay evaluated his design more than Chris did, which ultimately led to a significant iteration of the solution. Jay also spent significant time researching possible solutions to integrate into his overall concept, again, quite different from Chris. Jay ended his design activity with a critique of his design before declaring he was finished. Throughout his design activity, Jay did not explicitly justify the decisions he was making, but he was comparing his solution against what his goals were for the device. In the reflective part of the interview, Jay was able to articulate the assumptions he made, the criteria and constraints he was designing to, and could talk about pros and cons of his solution, though interestingly, he didn't discuss any of this during the live designing where he was moving very quickly through the activity. It is possible that Jay was stuck in system 1 (fast, intuitive thinking), and couldn't articulate all the thoughts he had in the moment but could describe what he did when asked about it shortly afterwards. There was evidence of this in two exchanges with the interviewer. In the first one, the interviewer asked if Jay felt there was any missing information in the instructions, to which Jay replied that it seemed complete, and he could just imply any missing information like what type of disability the user(s) had. The second was when asked what he would do differently if he redid the design activity. In Jay's response, he recognized that he made several assumptions at the start of the problem and would want to revisit the constraints and criteria to capture a wider set of users with his design. In hindsight, Jay could see the assumptions he made, and understood the impact they had on his process, but he was unable to consider them explicitly while he was actively designing. When asked how he would justify one of his design decisions to his boss at work, Jay was able to articulate 3 criteria: the design was made from flexible material improving its functionality, was inexpensive, and was ergonomically friendly without needing anything but the users' hands to operate. It is challenging to estimate with accuracy the level of King and Kitchener's model that Jay is operating at, however, based on his nuanced justifications given in reflection after the activity, it would seem Jay is operating in the

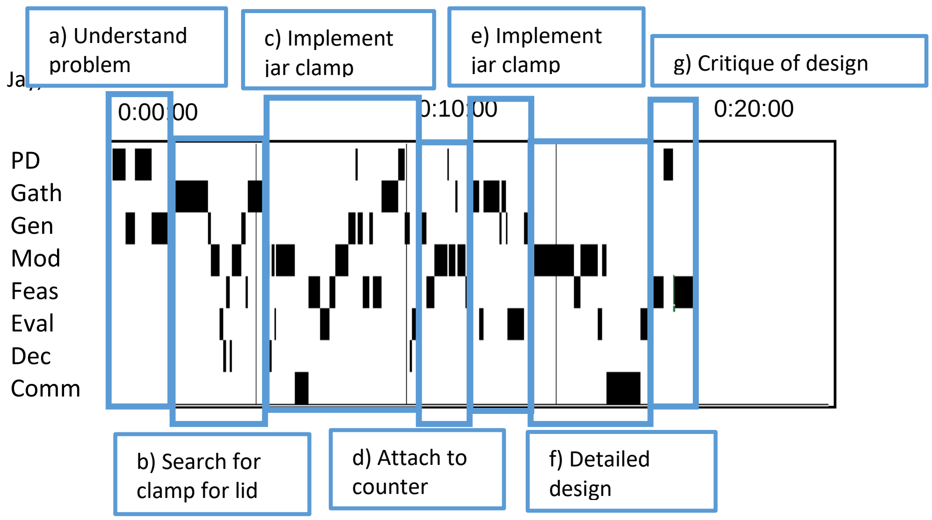


Figure 67 Overview of design process, 1A interview with Jay

Quasi-Reflective thinking stage, perhaps even level 5. There was little evidence of reflective thinking as Jay did not compare different solutions before deciding that his approach was the right one.

Figure 67 shows the design timeline for Jay. Jay spent 17% of his total time gathering information, 12% generating ideas, 10% of his time evaluating, but only 2% of his time making decisions. Jay demonstrated several of the indicators of informed designers including stating explicit design goals, researching the solution space, and revisiting design goals and evaluation of his solution against his goals in a more limited way. Jay has a similar level of prior experience to Chris, and interestingly their solutions had similar elements in that they both relied on an oil filter wrench as part of the solution, however Jay seems to have a more developed personal epistemology and demonstrated more behaviours that are indicative of an informed designer. Compared to Chris, Jay's justifications in the reflective debrief had nuance, but Jay was not able to articulate them during the live design activity. Perhaps Jay was rushing through the design activity, or perhaps the task was too complex to communicate his deeper thinking while he was designing his solution.

Bond

Bond has taken part in several activities that plausibly could have developed his personal epistemology. The most notable activity would be Shad Valley, that Bond took part in online in 2020. Bond himself admitted that he didn't take it very seriously, but when discussing the work that he and his group completed, it was clear that they were taking part in the same process that MJ described. The impact of moving the program online were two-fold: Bond missed out on the process of constructing a prototype of their design, and the opportunities for the social-based resolution strategies, and for reciprocal causation were likely lessened. One difference from MJ was that Bond conducted a significant amount of online research for his project and was more involved in the technical decisions that the group made. In addition to his Shad experiences, Bond spent considerable time and effort building different things including planes with his father, and surf/skim boards for himself and his friends. Bond described the many iterations of his skim board designs during the interview, and discussed the many lessons learned as he iterated and tried different materials like wood, fibreglass, and carbon fibre. Bond also spent time at a custom bike manufacturer making wheels for the bikes, where he also received mentorship from one of the company's designers. Taken together, these opportunities could each have provided Bond with epistemic climates conducive to developing his personal epistemology.

In the design activity, Bond (like MJ) began with a divergent thinking exercise to come up with different overall concepts for his device. Bond quickly transitioned into thinking about the overall function of the device and of criteria and constraints; all heavily influenced by the teaching in ME 100. As Bond continued in his designing, he iterated on and improved his design as he thought about its functionality, but he didn't stop to conduct the divergent thinking for the various sub-functions of his design to the same extent as he did at the start of the interview. In the debrief part of the interview, Bond recognized that the problem had more than one solution, and that there is no one way to solve this problem. Bond seemed comfortable with the ambiguity of the problem, he didn't think there were any missing instructions, for example, he knew that he would have to fill in the missing pieces based on the solution he chose. When asked about the assumptions he made along the way, he mentioned that he assumed a consistent size of jar (and that his device wouldn't work well for jars of other sizes) but couldn't really identify any others. When asked how he knew he had made the right decision in his selections later in the process, Bond didn't have a good answer and realized that he hadn't really thought about it in the moment: "umm because…. Um… I didn't think about. The reason I knew that I I knew I needed them because I went through that needs first." In the debrief, Bond was able to speak more about the pros and cons that led him to the overall approach early in the design activity but struggled to justify his specific design decisions from later in the process. Determining the level of King and Kitchener's model that Bond was operating at is challenging. Early on he had a fairly sophisticated set of criteria and broke the problem down by function. He didn't come up with a lot of alternatives to the approach he ultimately selected, but he did evaluate it against his criteria. In this earlier, slower, and more deliberate phase of his design process, Bond seemed to be showing reflective thinking (level 6). Later on, however, he got moving too quickly and even in retrospect he couldn't give good reasons for his decisions or really explain/justify the assumptions he made. As he got into the detailed design, Bond seemed to be operating in more a quasi-reflective level.

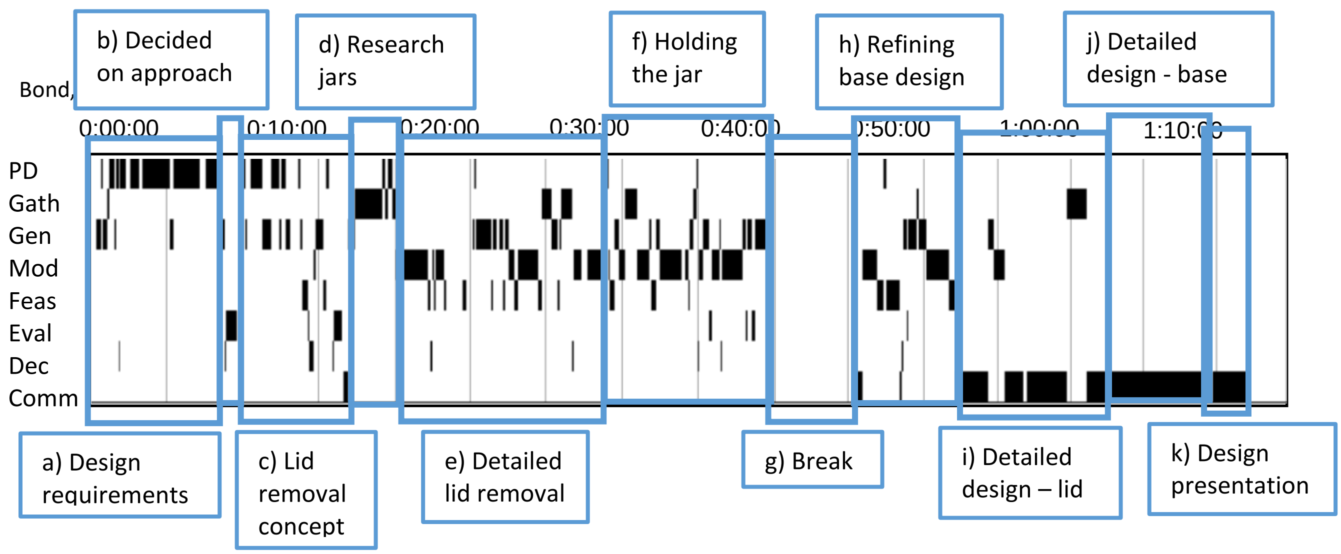


Figure 68 Overview of design process, 1A interview with Bond

Figure 68 shows an overview of Bond's design process timeline. Bond spent 8% of his overall time gathering information, 13% generating ideas, 2% in evaluation, and 1% in decision-making, and he demonstrated all the indicators of informed designers to at least some degree except for weighing benefits/trade-offs before making decisions. The lack of concept generation and subsequent lack of evaluation/justification in the later parts of the process seemed to be more a result of a lack of knowledge or confidence, as opposed to the impact of pre-reflective thinking. Once the overall concept had been selected, Bond seemed to shift into system 1 thinking where he got moving quickly through the process, making intuitive decisions along the way; Bond didn't slow himself down later in the process like he did at the start.

Jill

Jill had the benefit of participating in several open-ended activities during her time in high school. She took part in the airplane design and Rube Goldberg Science Olympiad competitions in grade 10. These activities were constrained by consistent rules for all participants, came with a lengthy manual of restrictions, and at least in the case of the plane design, a common starting set of components to construct the plane from. So, while the event wasn't fully open and ill-structured to the extent that the ME 100 toy project was, it seemed well set up for creating epistemic doubt and epistemic volition in the participants. The regional competition format also provided opportunities for resolution strategies and reciprocal causation as Jill interacted with judges/mentors and saw what her peers had created. Jill had also taken AP computer science in her Canadian high school, had completed some side projects programming encryption algorithms, and participated in a hackathon prior to university. Hackathons can create epistemic climates that are conducive to epistemological development because of their openness, opportunities for interacting with judges/mentors, and opportunities to observe and collaborate with peers.

Early in the 1A design activity, Jill compared two general approaches to the problem: a hand-held device that might be cheaper to construct but would require more physical ability from the user, and a more automated approach that would be more expensive but would have greater accessibility to a wider range of people with disabilities. Jill ultimately emphasized accessibility at the expense of cost. Unlike some of the assumptions and goals that Jay had, that were largely unstated until the reflective portion of the interview; Jill was cognizant of this trade-off while designing, and then expanded on it in the reflective portion of the interview. Once this decision was made, however, Jill did very little explicit evaluation or decision-making, instead spending the vast majority of the remaining time in modelling her solution. During this portion of the activity, Jill's process became very ad hoc; she was addressing design issues as they arose by making changes to her design until she declared the design was finished. Jill's early process showed evidence of reflective thinking as she decided on the general approach she would take with the design, however there was less evidence of that level of thinking as the design process progressed. For the bulk of the design process, Jill was operating at the quasi-reflective level (level 4), stretching to reflective thinking (level 6) early in the process when she was most comfortable.

Figure 69 shows Jill's 1A design process timeline. Jill spent 12% of her overall time gathering information, 14% generating ideas, 5% in evaluation, and only 1% in decision-making, and demonstrated several indicators of informed design behaviour including stating design goals, researching the problem and solution spaces, generating a range of concepts, revisiting design goals, and evaluating her solution against the goals. Jill has slightly more experience with the earlier phases of the design process than the later ones; hackathons are great at providing a space to practice the start of the process, but solutions are rarely developed to a working prototype. That sort of experience is consistent with what Jill showed in this interview; her process was more expert-like in the starting phases, and less expert-like as she worked on the detailed mechanical and electrical design of her device. It is possible that for Jill, her epistemology may have led in the early stages where she was more comfortable, but once she began the detailed design of her device and ran out of knowledge, the quality of the process declined. So, while Jill came up with options and evaluated which option she wanted to pursue for the overall solution concept, she did not do the same thing when it came to the sub-problems of her device (like holding the base of the jar steady). Interestingly, Jill realized she could have done more evaluation (and iteration) in the reflective portion of the interview at the end, which may have led to an improved overall design.

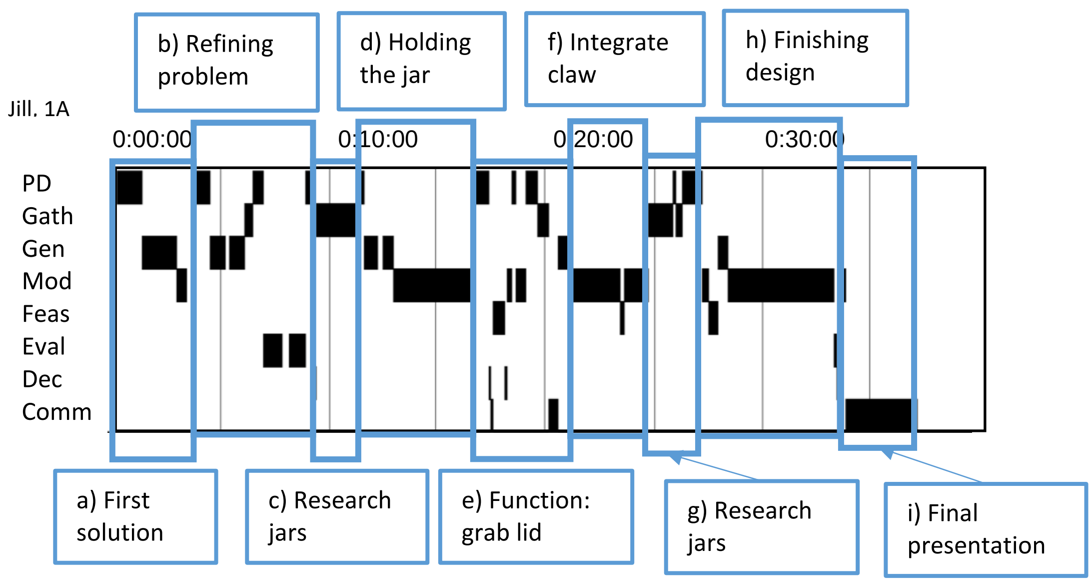


Figure 69 Overview of design process, 1A interview with Jill

Appendix H Detailed Data – 1B Personal Epistemological Development

Jill

Jill felt ME 100 was the only 1A course with open-ended projects or assignments. She remembered both the toy project, and the cell phone stand project. For the toy project, Jill's team had a clear concept for their toy which seemed to help with their design process as they had a clear target for their prototype. The team seemed to have a solution which they felt would work for their toy prototype, and they were given an alternative by the toy company client that the experts felt would work better than what the student team was proposing. This seemed to cause Jill and her team some trouble as they wanted to use the advice but were unsure about switching concepts partway through the project. After talking with the teaching team, they were convinced that there wasn't enough time left in the project to pivot to a new concept, and so they continued with their original idea. Jill remembered the concepts of criteria and constraints from ME 100, and she talked briefly about trade-offs in design and how different contexts can create different priorities for the designer. She gave a couple examples of how a context can prioritize certain criteria, but the examples tended to have little nuance (e.g. for a device that is being made for use in space, cost is not a priority). Later in the toy project, Jill's group struggled to get their prototype to work, and she described an interaction with the DCAP instructor where he seemed to give advice that contradicted something he said earlier in the term, which confused Jill: "[DCAP instructor told us] If you want a pipe go buy a pipe. Do not 3D print a pipe so we did not 3D print a pipe and then on the day of the symposium… He offered to help us out and he was like we could've 3D printed the pipe and I was like… OK. if I had 3D printed, it probably would have been like a pipe split in half [to make assembly easier]. So yeah it was kinda funny in the moment I was like I thought we weren't supposed to 3D print pipes". For the cell phone stand project, Jill felt the material constraint was challenging to work within, and it seemed be the primary driver of the design decisions she made. Jill was also able to see what some of her friends designed for the cell phone stand as they worked on their designs together. From the discussion about ME 100, it seems like there were a few opportunities for Jill to experience epistemic doubt, however she did not seem to take the epistemic volition to change her beliefs.

In addition to her experiences in ME 100, Jill also joined a student design team in her 1A semester. Jill joined the mechanical sub-team of a group that was designing small space satellites, and in this role, Jill was able to complete two rounds of CAD designs on a custom chassis for the satellite. The first design was of a “1U CubeSat” which is a cube 10cm on a side, and the second design was of a 3U CubeSat (which is the equivalent of 3, 1U CubeSats side by side). The smaller design was used by the team as early training for a new team member, and Jill leveraged that experience in the 3U design that she completed over the December holidays. When she returned in January, an upper year student on the team reviewed her design and gave her feedback. Jill saw this design task as very open-ended and used the simpler design of the smaller satellite as a starting point for the larger, more complex one that she designed herself. Jill also worked on a side project prior to the 1B interview: a “spinner” ring that she was planning on 3D printing as part of her training with the student team. When talking about the ring, Jill mentioned that she was designing it for a friend of hers, but she was enjoying the process of making all the design decisions herself. Much like with her cell phone stand project, she was the “client” for the design solution, and so she didn’t have to weigh the desires of an outside client in her process. Both experiences were no doubt good practice for Jill’s design knowledge and skills, but it is not clear how effective they were at developing her personal epistemology. The student design team setting, with the more complex, real-world design problems was more likely to cause epistemic doubt as she observed older peers designing, and there were opportunities to discuss the designs with some older students (representing a potential resolution strategy), but its not clear if Jill had the epistemic volition, or meta-cognition to question her own beliefs.

In the design activity, Jill spent some time early in her process thinking about why the window would be stuck, recognizing two sub-problems: the tracks could be dirty and needed to be cleaned, and the window might need more force applied to get it moving again. She listed a couple options for applying force to the window sash, but quickly selected a motorized pulley system with no justification or evaluation of the other options. In her later decisions, like incorporating compressed air canisters and lubricant to clean and lubricate the window slides, or in her decision to permanently attach her device to the window, Jill did not develop any alternative concepts and provided only the barest justification for the selected concept. Jill spent quite a long time researching the operation of the double-hung windows, but she did no research of anything relating to her solution. Late in the design activity, Jill discussed some of the choices she made which seemed to be mostly driven by her evaluation of the device’s aesthetic qualities, however she did set out design goals to have the device be usable by a wide spectrum of users (i.e. maximize the accessibility) and be safe for the window to install and use.

In the debrief, Jill was not able to identify alternative concepts that she considered in the design activity, and when asked to justify the choice to have her device permanently installed on the window, she felt this was easiest for a disabled user as it is installed once and then they can just use it when they need it. The only source of uncertainty she could recognize was that she didn't understand the operation of a double hung window; a point she reiterated several times in the debrief. Jill felt that the design problem had more than one solution, and when asked if there is a "right" answer in design, Jill said no, and commented: "If like it was a given that, oh, you cannot make it motorized, or like you cannot make it hand pulled or you… don't have to worry about it being clean or not. Like those statements, they will produce a different design outcome". From this comment, it seems like Jill is recognizing the importance of context on design outcomes, but it is unclear who would state any of these requirements, and it seems like Jill is looking for someone else to tell her what is important in the context. Jill discussed this more explicitly when asked how she would justify her design to her boss, stating she would want the boss to tell her what the design priorities were. When asked how she would select between her design and someone else's design to solve this problem, Jill walked through a typical structured decision-making process taught in many introductory classes: Check if it meets the constraints, then prioritize your criteria and rank the two solutions. From this brief discussion, it seems like Jill knows and understands a process for comparing two designs, she just didn't do that in the design activity. Overall, Jill seemed to be demonstrating mostly level 3 pre-reflective thinking, though perhaps occasionally level 4 quasi-reflective thinking. Jill was looking for an expert, or a superior to prioritize the design criteria so Jill could design a solution that would fit their expectations. As Jill described how she evaluated her toy project, the cell phone stand, and again with the 1B design activity, she was only verifying the operation of her solution against the most obvious/important design constraints, and so seemed to avoid considering any trade-offs in her chosen solution.

Figure 70 shows the timeline of Jill's design process in the 1B interview. Overall, she spent 20% of her time gathering information, 9% of her time generating ideas, 4% evaluating, and 0% making decisions. In 1B, Jill demonstrated 3 indicators of informed designers (stating design goals, researching the problem space, and evaluating the solution against the design goals), and 2 more in a more limited fashion (generating a range of concepts, and creating detailed drawings). This is in contrast to 1A where Jill demonstrated 5 fully (stating design goals, researching the problem space, researching the solution space, generating a range of ideas, and revisiting design goals), and 1 in a more limited way (evaluating the solution against the goals) – perhaps a regression in performance. Jill seemed to be less sure of herself in the 1B activity, perhaps due to her not understanding how a double-hung window operates; Jill mentioned several times in the debrief that not understanding the operation of the window was a source of uncertainty for her.

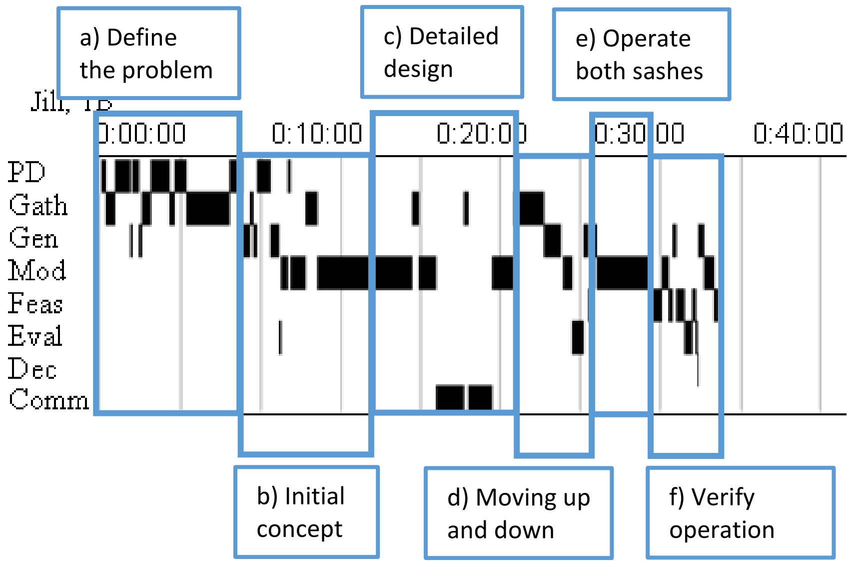


Figure 70 Overview of design process, 1B interview with Jill

<u>Jay</u>

Jay's only memory of open-ended design problems in his 1A academic term was the ME 100 toy design project. When asked how his group navigated the openness of the problem, Jay's group came up with a long list of possible projects, narrowed it down to a smaller list that they felt were good, and then asked the TAs and professor which one they thought was the best to pursue. When asked more about this, Jay clarified that the teaching team really helped his group eliminate ideas that were not possible given the time they had, and their knowledge level. When asked how he knew the group had made the right choices in the project, Jay commented: "I don't. I'm not sure if we really like found the best solution, but we just found the solution that would work for us. It was typically the one that required the least amount of work. The simplest option, the one that required us to buy the least amount of materials." Jay was asked directly about the cell phone stand project, and he remembered it, and stated that it helped him understand how to incorporate design tools like SolidWorks into the design process, but he took away few other lessons from the project. Jay's other relevant experience from 1A was participating in the formula motorsport student design team. Jay's work with the team was in the aerodynamics group, and in 1A he learned a bit about simulation tools and helped construct some of the carbon fibre parts for the car. While part of this team, Jay was able to observe how upper year undergraduate students design and validate parts through simulation. These upper years would also provide feedback to Jay as he worked on problems for the group. Jay's 1A experiences did not seem to provide many opportunities for epistemic doubt in Jay, limiting the impact of even the open-ended design projects on his personal epistemological development.

Jay's co-op work term was at an automotive parts manufacturer, where Jay conducted testing to validate the performance of parts the company was designing. This experience gave Jay the opportunity to witness the design process of the professionals employed at the company, including how they iterate on designs, provide feedback to each other, and test and validate the performance. Later in Jay's work term, Jay's manager at the company gave him the autonomy to design the component tests with limited supervision and would then just verify the setup before Jay conducted the tests. When asked if Jay ever disagreed with feedback from the others at his company, Jay commented: "Well, usually since I'm still like really inexperienced versus this person who's probably been in the industry for, like, my whole life, I would always sort of err on the side of them being correct. And then because there's probably some hidden thing that I haven't seen yet. And so usually I'll just try to adhere to their solution even if I didn't necessarily agree with it at first and because usually it works out at the end anyways." While this comment reveals a deference to authority in stating the accuracy of a course of action, it also reveals a power dynamic between Jay and the more experienced employees at the company, where Jay did not feel he was able to speak up about his doubts. Jay's work term seemed to provide opportunities for epistemic doubt, and from Jay's description, his manager was present to discuss Jay's work throughout the work term (and thus provide a resolution strategy), it is not clear that Jay ever took epistemic volition to question his own beliefs.

Early in the design activity, Jay decided to simplify the problem to just focus on the movement of the lower window sash, and to ignore the tilting mechanism. This behaviour is reminiscent of how he described the process of making project decisions in the 1A toy design project. Jay justified ignoring the tilting mechanism largely due to his lack of understanding of how it operates. Shortly after that, Jay discussed his reasoning for the main motion of the user to be a downward pulling motion on his device because he wanted to accommodate disabled users who may be in a seated position – a much stronger justification than he provided earlier, even though he didn't really mention what other alternatives he was thinking about (if any). Around the 10-minute mark, Jay communicated the first and only pair of options he could pursue: having chosen the main mechanism for his solution, he needed to decide if the device he was designing was permanently installed, or only installed when it was needed. Ultimately, he selected a permanent installation because he felt disabled users might struggle to install a temporary device. Near the end of the activity, Jay turned to the interviewer to ask how the windows operated in more detail (as opposed to searching online). In the final section of the activity, Jay communicated the next steps he would like to take if he was going to continue working on the solution – steps which largely consisted of iterating through the use of physical prototypes. Jay did not seem to have another method for making decisions or iterating on his design.

During the debrief, Jay was asked about the process he used to solve the problem, and how he selected that process. It was clear from the discussion that followed that even though he was in ME 101 at the time which is teaching a slightly different design process from ME 100, he really hadn't absorbed the procedural knowledge taught to him in either course, and so didn't see alternative methods for solving the problem. When asked about his design goals, Jay was only able to articulate safety for the user – a constraint that may have caused him to over-correct in his solution where he included a lock on the upper window sash, rendering it inoperable, in case it fell and hurt the user. When asked, Jay was not able to identify any trade-offs in his design except for the additional mechanical complexity his solution adds to the window. When asked what his work term taught him about design, Jay commented that it taught the importance of iteration on improving a solution; something that he did try to enact in his process as he thought about some of the weaknesses of his design. Lastly, during the debrief, Jay reiterated some of his comments from earlier in the interview; Jay would justify the choices he made based on his perceived lack of knowledge of the other alternatives (like avoiding an electro-mechanical solution, for example).

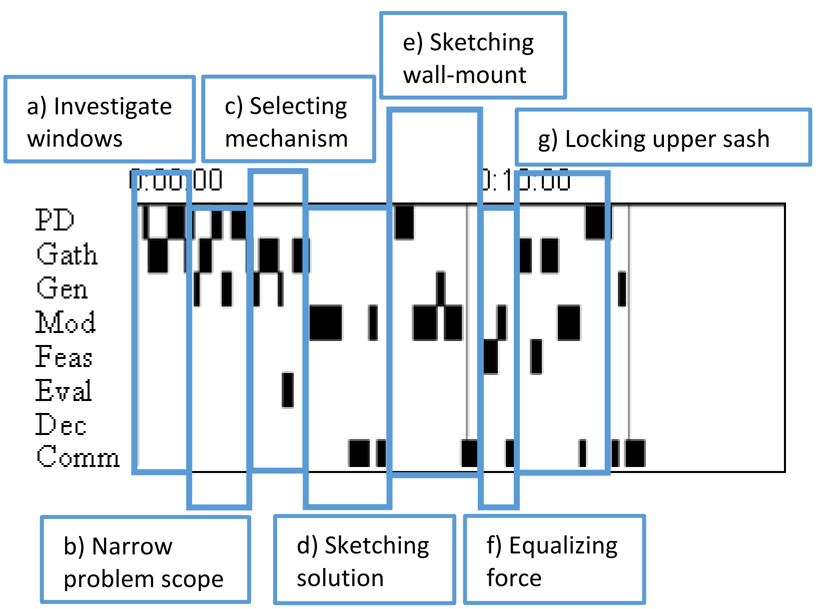


Figure 71 Overview of design process, 1B interview with Jay

Figure 71 shows the timeline of Jay's design process in the 1B interview. Overall, he spent 21% of his overall time gathering information, 7% generating ideas, 2% evaluating, and 0% making decisions. Jay demonstrated 1 indicator of informed designers (researching the problem), and 3 in a more limited way (setting design goals, researching the solution space, and evaluating the solution against the design goals), which represents a small step backwards from 1A where he stated goals, researched the solution space, and revisited goals, and to a lesser degree, evaluated his solution against his goals. Overall, Jay's behaviour was indicative of level 3, pre-reflective thinking, with elements of level 4, quasi-reflective thinking. Jay struggled to identify any trade-offs in his presented solution, but he could recognize some decisions he made, and was able to give relatively weak, idiosyncratic justifications. Mostly, Jay's choices in the design activity seemed to be mostly for his own benefit, aimed at simplifying the problem as much as possible to make it easy to solve.