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FOR WHOM ARE WE PROTOTYPING? A REVIEW OF THE ROLE OF CONCEPTUAL PROTOTYPING IN ENGINEERING DESIGN CREATIVITY

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Abstract: Prototypes are made, presented and interpreted differently by people according to their understanding and frame of reference. Design educators have, in recent decades, come closer to one another in how design creativity is approached. Still, many distinct differences exists. One of the most striking has to do with the role of prototyping in transporting ideas into concrete manifestations. Prototypes unlock cognitive association mechanisms related to visualization, prior experience, and interpersonal communication in ways that favour iterative learning between peers in the product development community. When, where, and how to use prototyping strategies depends on context and demands a high level of situation awareness. The nature of this awareness is in turn dependent on cultural variables. This paper investigates how prototyping is perceived in two distinctly different high performance academic contexts (i.e. Stanford and KTH). In both cases we have studied how prototyping enables new knowledge to emerge through iteration and team-based communication. The paper focuses on student's perceived learning experiences and on teacher's experiences within engineering design projects. Building on related research, this paper establishes a link between embedded implicit knowledge and its consequences for objective learning.

Keywords: *Prototyping, design creativity, collaboration, knowledge, learning*

1. Introduction

To create tomorrow's innovations we are in need of engineers that thoroughly understand what design creativity entails (Dym et al., 2005; Sternberg & Lunbart, 1999). Creativity in the context of engineering design activities is linked to problem solving and other cognitive activities. Design creativity is consequently approached through an array of feasible alternatives, any one of which has the potential to be the final product. Engineering creativity then requires a special set of skills for: 1) what to prototype; 2) chosing the appropriate prototype media; and 3) placing the prototype in the most advantageous framework for its audience and creators. Cognitive attachments or aspects thereof provide prototypes with a common language, a knowledge statement that simply can be shared. Research from learning sciences shows that prior knowledge plays a critical role in how students progress through a problem, what they learn, and what they produce (NRC, 2003).

Prototypes can be roughly categorized into two distinct formats: physical and analytical (Ulrich & Eppinger, 2007). Physical prototypes are tangible approximations of the intended product, whereas analytic or ‘virtual’ (Liou, 2008) versions are more commonly used to create a detailed and mathematically correct model of a specific product component. High resolution virtual prototypes are perceived to be flexible and easily modified, a factor which facilitates accuracy when adjustments are made to vital data needed for predictions. Predictive power assures confidence in the modeling process (ibid). In contrast physical prototypes still carry an important role of illustrating and communicating functionality. In a way that might seem counter intuitive, low resolution prototypes foster divergent thinking about the nature of the problem and the solution (Edelman 2011). This form of communication is particularly relevant during periods of rapid change in the evolution of products and services. This is almost always a requirement in early development stages and can still play an critical role in advanced stages where circumstances demand change.

Prototypes serve several purposes: they function as guiding milestones; show tangible progression or demonstrate specific features; and enable systems integration, ensuring components and subsystems work together as planned (Chua, Leong & Lim, 2003). Prototypes externalize thoughts and make people talk, but the dialogues between people and prototypes is more important than creating a dialogue between people alone (Cross, Christiaans & Dorst, 1994). Depending on the type of design, prototyping can take on different forms and yet denote similarities in the final manufactured form. Prototypes allow ideas to emerge from tacit formats. Learning is influenced through integrative skills and problem-solving modes (Pisano, 1996). In consequence, the activity of building prototypes and communicating through prototypes, has a central role in all phases of a product development project (e.g. viability testing, sub-system functionality, proof of concept).

For engineers, idea generation and prototyping can be merged through ‘hands-on’ activity. In parallel with other idea generation methods, prototyping defines lateral thinking where divergence and systematic thinking are unified (von Hippel, 1988). Prototyping supports ideation, conceptualization, design exploration, evaluation, communication, and construction. Because it can be an overwhelming undertaking to create a single prototype that strives to achieve all of these goals, it's important to be focused about objectives. From an educational viewpoint, achieving learning objectives overshadows the importance of technical performance even though they tend to go hand in hand. Past studies argue that reflections on the functionality and role of prototyping in engineering education need greater attention (Cross, Christiaans & Dorst, 1994; Chua, Leong & Lim, 2003). In consequence, this paper seeks to further delinate the ways in which prototyping drives context-dependent learning in engineering theory and practical education.

2. Prototyping from a holistic perspective

The unique strength of the prototyping model lies in how it facilitates communication between people, especially across disciplines and roles. Conceptual prototyping (to distinguish it from manufacturing prototyping) leads to shared experiences; tangible collaboration with others; buildings understanding through experimentation; and demonstrates a range of feasible manifestations. Prototypes function as carriers of both static and dynamic knowledge. Efficient and timely knowledge transfer always facilitates the new product development process. Recognizing that prototyping is a meta-cognitive activity that externalizes knowledge we find that it fits well with Nonaka's argument: *‘While tacit knowledge held by individuals may lie at the heart of the knowledge creating process, realizing the practical benefits of that knowledge centers on its externalization’* (Nonaka 1994).

The kinds of knowledge that are generated through this iterative work process has been addressed through reference to a variety of different taxonomic types (Nonaka & Takeuchi, 1995; Nonaka, Toyama & Konno, 2000). Different ways to formulate a knowledge sharing taxonomic approach is to identify specific conditions that facilitate knowledge exchange (Nonaka, Toyama & Konno, 2000). Iterative prototyping promotes a wide range of knowledge exchanges that are context and learning requirement dependent. In conveying knowledge, it is helpful to understand the binary nature of knowledge; namely that can be simultaneously objective and subjective (Brown & Duguid, 1991). And more, the consensus/dissensus dimension orients participants towards different aspects of scientific discourse, e.g., normative, interpretive, critical, and dialogic (Alavi & Leidner, 2001). Prototypes are objects (virtual or physical) that shift in character similar to how knowledge representations are perceived to exist as objects; explicit or factual knowledge and tacit or ‘know how' (Schultze & Leidner, 2002). The fluidness of knowledge brings distinctive perspectives into dialogue through the construction and visualization of boundary objects (Carlile, 2002) through prototype cascades (Edelman, 2011).

The dynamics of knowledge creation and the need for a platform of understanding argue for a knowledge perspective to be in place for successful knowledge transfers (Nonaka & Takeuchi, 1995; Nonaka, Toyama & Konno, 2000). The interrelation of individual and collective knowledge is proposed to be a generative source for accumulating successes, where stories and externalized means (e.g. prototypes) carry meaning to a specific group of people (Brown & Duguid, 1991).

In this process inter-functional communication and co-ordination depend heavily upon the effectiveness of non-articulated translation and integrative procedures. Similar to the anecdote of the knowledge iceberg (Polanyi, 1958; Stenmark, 2000), where communicated and shared knowledge merely accounts for the visible surfaced representations, prototyping shares this dualistic imperative. Collaborative and individual manifestations are dealt with in either virtual or physical shapes where the knowledge dealt with in one mode might be difficult to transfer to the next. However, iterations form prototypes that function as lateral manifestations leading towards perfection. This involves a combination of both 'explicit' collaborative learning aspects and hidden 'tacit' affordances that allow for intangible propositions to be processed, understood, and manifested.

Knowledge is socially sourced and constructed through social processes, including: access to guidance, observation and interactions with peers; and shared workplace artifacts (Valsiner, 2000). Given the social roots of human knowledge, interaction between peers is crucial to the creation and reshaping that is manifest in boundary objects that allow for perspective taking and knowledge transparency overall (Boland & Tenkasi, 1995).

Based on double loop learning (Argyris & Schön, 1978), the challenge and redesign of existing knowledge requires cognitive reframing. Prototyping allows embedded knowledge to take part in the re-appropriation of, and integration of, *sticky information* (von Hippel, 1994). Prototyping meets the requirements of lateral thinking and creative communication.

3. Prototyping manifests experiential learning

Experiential learning deals with conflicting dualities as complex mental processes are perceived and translated into knowledge categories: *active experimentation* and *reflective observation* (Kolb, 1984). Summarizing Kolb's ideas, active learners relate to testing beliefs through external methods and explanations in some way, whereas reflective observations involve examining and manipulating information introspectively. Notably, experiential learning juxtaposes two fundamental differences in how to learn from experiences (concrete experience and abstract conceptualization) and two approaches to transforming experience (reflective observation and active experimentation). Kolb uses a two-by-two matrix that provides a dichotomatic categorization of four learning styles: diverging, assimilating, converging, and accommodating. A diverging style is good for idea generation activities, while individuals that have preferences more related with a converging style prefer technical tasks over tasks dealing with social or interpersonal issues. The assimilating style relates to individuals that are 'information-brokers', meaning good at taking in a lot of information and logically ordering it. Finally, hands-on experience and action-oriented learning is best matches the accommodating learning style.

Active learners are experimentalists, and good in performing work in collaboration with others, whereas reflective learners are theoreticians, and like working by themselves or in micro format groups with just one other individual (Felder, 1988). Indications say that engineers are more likely categorized as active learners (ibid), rather than reflective learners which correspond well into the role of an engineer, which is to engineer, build (Crawley et al., 2007).

Reassuringly, a proper understanding of the application of prototypes to target individual assessment and ability to learn. In similarity to past research (Argyris & Schön, 1978), individuals will have learned but the organization will not have. Through prototyping, intangibles are decoded and understood by individuals working together. Unfortunately these knowledge constructs face disabling intra-group transfer limitations that can block collaborative consensus. Prototyping as a mean to evoke an action based knowledge state, or status of *'knowing in action'* (Cook & Brown, 1999) provoke different ways of assessing the role of what is known in an organization's ability to learn, to maintain quality, to develop competencies, and ultimately to innovate. The use of prototyping and tools that have an integrating function have shown a mismatch between the application of specific tool and the functions intended (Ballie & Moore, 2004; Norell, 1998). Therefore, to have successful use of prototyping it is essential to overcome obstacles and weaknesses involving individual learning, efficiency in task functional collaboration and work orientation modes.

In the daily workplace prototyping is an activity that can override dysfunctional communication structures, and align knowledge representations in a shared collective representation. Methods and techniques that aid engineers in their daily work need early up front practice to have any considerable impact on work processes and target audiences. Prototyping in particular carries perhaps a greater value as knowledge repository than work practices is sometimes able to reveal. Without 'good enough' exploration of the design space in search for suitable alternatives subsequent design stages (e.g. analysis, testing, decision making) have no significant impact.

One key to bring about a reflective perspective and deepen the learning process for the individual would be to re-think and re-frame on-going negotiating design processes. Understanding about the learning process, how it works from a practical viewpoint, may substantially increase the chances of developing and applying these abilities later in life (Eris & Leifer, 2003; Cross, Christiaans & Dorst, 1994; Felder, 1988).

4. Prototyping in knowledge communities

The university environment supports a rather controlled knowledge community where procedural approaches and collaborative traits can be found in engineering design projects. Tasks that herein reinforce project experiences and learning cover an ambiguous number of designated work practices, e.g. determine project requirements, benchmark alternatives, conceive solutions, and the designing of incrementally more sophisticated prototype modes, analysis, needfinding preferences, user testing, team building, project organisation, capture and re-use of domain specific knowledge. From both industry and academia this is seen as the bridging component of the 21st century in working for promoting professionalism by students through prototyping.

Prototyping involves co-ordination of different knowledge types and levels, (e.g. formal/informal, local/global, tacit/codified, personal/social and software-embedded/people-embodied), where productive inquiries generate new knowledge and *knowing* (Brown & Duguid, 1991). In this process every *new item* refers to a new piece of knowledge and a *new way* that an individual decides to act with it relates to an individual's *knowing* (ibid). Similar expressions in engineering education literature often use labels as *functional knowledge* (Argyris & Schön, 1978), pragmatic *skills* (Crawley et al., 2007). Acquiring in-depth engineering skills corresponds well to what is claimed as *procedural knowledge* (Billet, 1996), where knowing *how* provides a basis for cognitive development.

The design phase is associated with several iterative loops that confront existing prefabricated knowledge expressions. To achieve optimized learning iterations each loop should opens up new opportunities where surprising elements can appear. To optimizeknowledge transitions between the learner and the facilitator is to embrace a repertoire of learner's actions of re-framing, listening, reflecting, engaging in dialogue, and trying again (Schön, 1983).

The integration efforts by students working together are evident, as collaboration allows more of their colleagues' input into their own subsequent concepts. Vice versa, colleagues also appreciate a more useful feedback to their creative thinking and prototyping efforts. In consequence, prototyping provide a tangible expansion to the generic understanding between interacting peers. From an agent-based view, individuals learn as part of a greater facilitating environment, and as part of an organizational learning environment (Adler, 1990). Our view is that this hub facilitates elements and distinctive actions (e.g. prototyping) that is transferable between the relationship of a single individual and a collaborative team. The learning progression in this somewhat chaotic process underpins an engineer's pragmatic skills (Crawley et al., 2007) and functional knowledge (Ballie & Moore, 2004) through adaptive and renegotiable conditions.

5. Different cognitive experiences to design

Academia recognizes an increasing trend where student participation in the learning process is developed through teaching and learning strategies that fosters distinctive skills that are rooted in academic achievements (Humphreys et al., 2001; Crawley et al., 2007).

The range of personal transferable skills that students need to be able to display include: communication and presentation skills; problem-solving and organizational skills; teamwork skills; and leadership skills (Sheppard et al., 2004). In such setting engineering design students are incorporated in industry sponsored projects to determine project requirements, benchmark alternatives, conceive solutions, and develop a series of increasingly sophisticated prototypes, analysis and user testing. The emphasis on student work in teams also reflects decades of research in higher education that indicates that collaborative learning, particularly when engaging students in complex engineering design projects.

In a comparison between American (Stanford University, USA) prototyping experiences and Swedish (KTH, Royal Institute of Technology) course outlines a fundamental difference is striking – prototyping is used differently as a learning tool dependent on variation in culture, way of approaching the phenomena and overall attention from faculty to establish innovative design. The Stanford University's ME 310 corresponds to the need driven engineering education where pragmatic skills need to be more closely aligned with team-playing and project-/problem-solving approaches (Sheppard & Leifer, 1997). ME310 prototyping are 'iterations', all intended to accelerate learning and cycle through the Kolb learning modes repeatedly at varying levels of abstraction. The common names of these prototype-assignments include:

1. critical function/experience prototype
2. dark horse prototype
3. funky-function prototype
4. functional prototype
5. penultimate prototype
6. final (turn it in) prototype

Both courses are described as rooted in providing students with opportunity to define and build a complex product component or system from concept to a functional prototype (Leifer, 1997; Norell, 1998; Berglund, 2008). Rather than challenging students with isolated mock-up scenarios, students are set out to define their own problem framing, including project requirements and build solutions for real companies. Prototyping is used as a continuous learning tool involving iterative feedback-loops with peers. This process allows critical questioning and community of inquiries that somewhat slows down the progression but simultaneously bring more depth to each step taken. The way in which up-dates, verifications and overall progression are taking is paraphrased by a ME310 student as *'we test a lot of different things; this makes us really understand different ways of approaching our solution space'*.

The practical aspects of both courses function as a suitable and harmless training ground, where students pick up new experiences simply by doing and redoing. Collaboration as part of the interaction with other engineers is placing the complete design related experiences in a pragmatic spot of how to conduct product development work as engineering designer in a real life context. Among students and faculty the ambition is to bring newness, blending different techniques with one another to reinforce individual skills as well as collaborative efforts. Educational schooling preferences attain collegiate equilibrium where pragmatic knowledge is put into practice.

At the KTH Royal Institute of Technology the IPD Master's level project course embraces a similar pragmatic approach as ME310 but with two distinct differences: 1) Rather than a distributed team set up a large team of approximately 15 students highly dedicated to the process oriented nature of prototyping refinements, 2) Prototyping is used less as a mean to communicate early up-front ideas, and more as an extension to first round data analysis and information gathering.

Still, as the KTH students come to a gate delivery in the ideation phase the 2D sketches have turned into both computer aided design captures and numerous 3D mock-ups. Explained by one student as; *'we catch up with new ideas, and angles to things we did not think of earlier when we get to materialize our thoughts'*. In terms of differences on learning style – a diverging style that allows time-on-task and for students to break-apart and reorganize, refruitalize existing beliefs is more tangible already in early phases through the existence of prototyping deliverables at Stanford compared to KTH. The systematic approach sought for by scholars (e.g. Dym et al., 2005; Crawley, 2007) runs like a machinery by the fifth year, where KTH students in particular have developed a self-regulated artistery that encompasses all four learning styles (Kolb, 1984). The most apparent difference relies in the pre-course set up, i.e. how much creative freedom and predefined workspaces that is provided upfront.

6. Conclusions

The way prototyping is portrayed in educational context may well carries a unique approach to manifest design creativity and to combine different knowledge aspects. How prototyping is perceived and learned is an issue of assessing and understanding it. The way in which students manifest creative experiences is perhaps best portrayed through the iterative process that students undertake to sophistically play with prototypes. A process that should be sought after as it stand a chance to wake up the unexpected instead of confirming the findings of what is previously known. Prototyping allows illustrative examples to take form, where the intangible is put in a context that can be interpreted by a multitude of individuals and create a vast perspective as part of a common language. Different ways of dealing with prototyping in design learning situations exists although they all intend to create knowledge about how to implement and apply suitable methods and tools. In this paper our ambition have been to present a multifaceted perspective of prototyping as a cognitive augmentation to design creativity practices. Although different approaches in how to learn the tangible aspects of design creativity a number of versatile approaches can bridge individual creative dispositions. We propose that future research could investigate the individual differences in greater detail. This would tune how different type of individual shifts could be mapped according to learning activities and distinct learning objectives cross different working contexts.

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