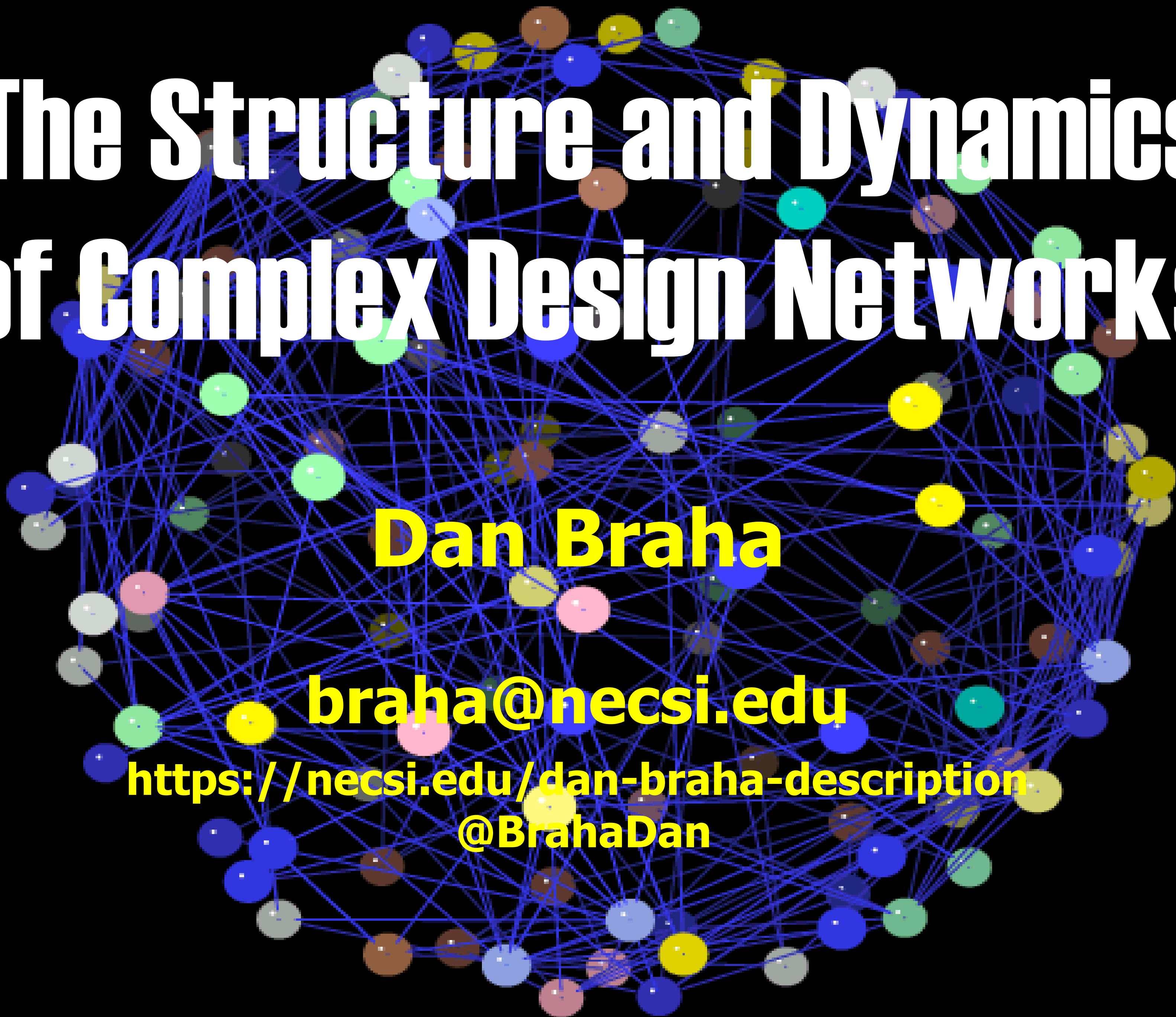
The Structure and Dynamics of Complex Design Networks



Dan Braha

braha@necsi.edu

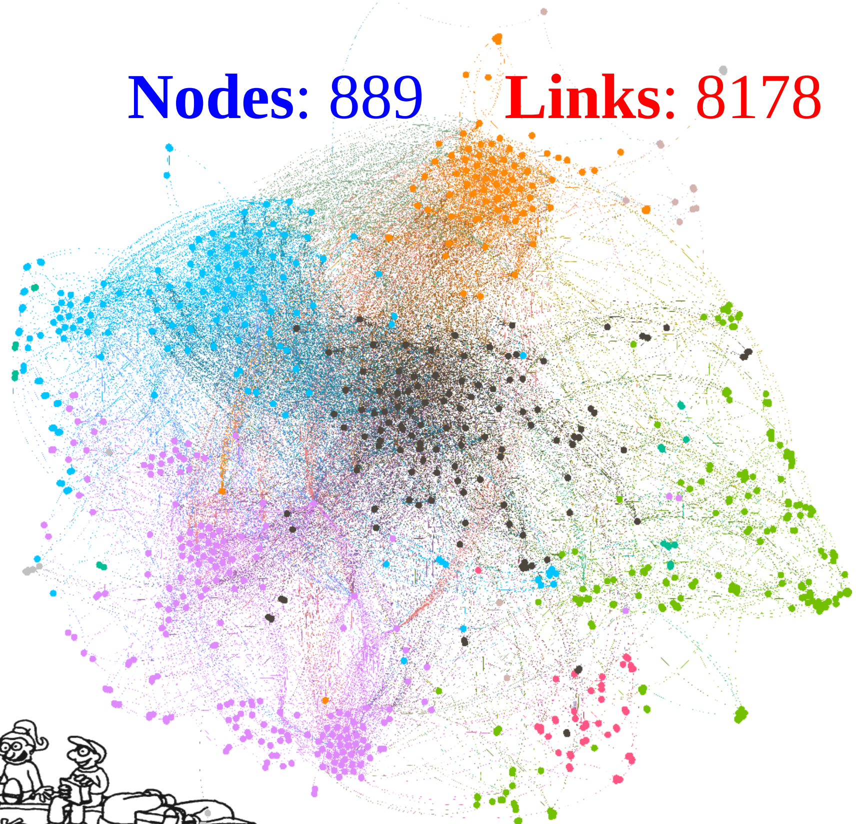
https://necsi.edu/dan-braha-description

@BrahaDan


(Press on nodes to see "linked" slides)
Literature on Design Iterations
Design Structure Matrix
Closure Topological Spaces and Category Theory
Literature on Design Thinking/Theory (e.g., C-K Theory)
1997 Philosophy of Science and Design
Module/ Relationship Representation of Artifacts
2003 Generalized Design Structure Matrix and Complex Concurrent Eng.
Closure Topological Spaces: 2003 RED's extended CDP topological model
Yoshikawa's General Design Theory: Point-Set Topology
Dan Braha and Oded Maimon
A MATHEMATICAL THEORY OF DESIGN: FOUNDATIONS, ALGORITHMS AND APPLICATIONS
APPLIED OPTIMIZATION
1991-98 Formal Design Theory (FDT)
Modularity in Design
Literature on Design Modularity
2003-21 Complex Design Network Theory
Measurement of Design Structural and Functional Complexity
Information Theory and Design & Guided Heuristics
Modeling the Evolutionary Design Process: CDP Model
1993 Universal Design Automata And Logic
Complex Network Theory
2006-10 Temporal Network Theory
2006 Complex Engineered Systems
Literature on Complex Design Networks and Engineering Systems
Literature on Measurement of Design Complexity
Correctness and Computational Complexity of Design
Design Paradigms AI in Design

Complex Design Networks

Nodes: 889 **Links**: 8178



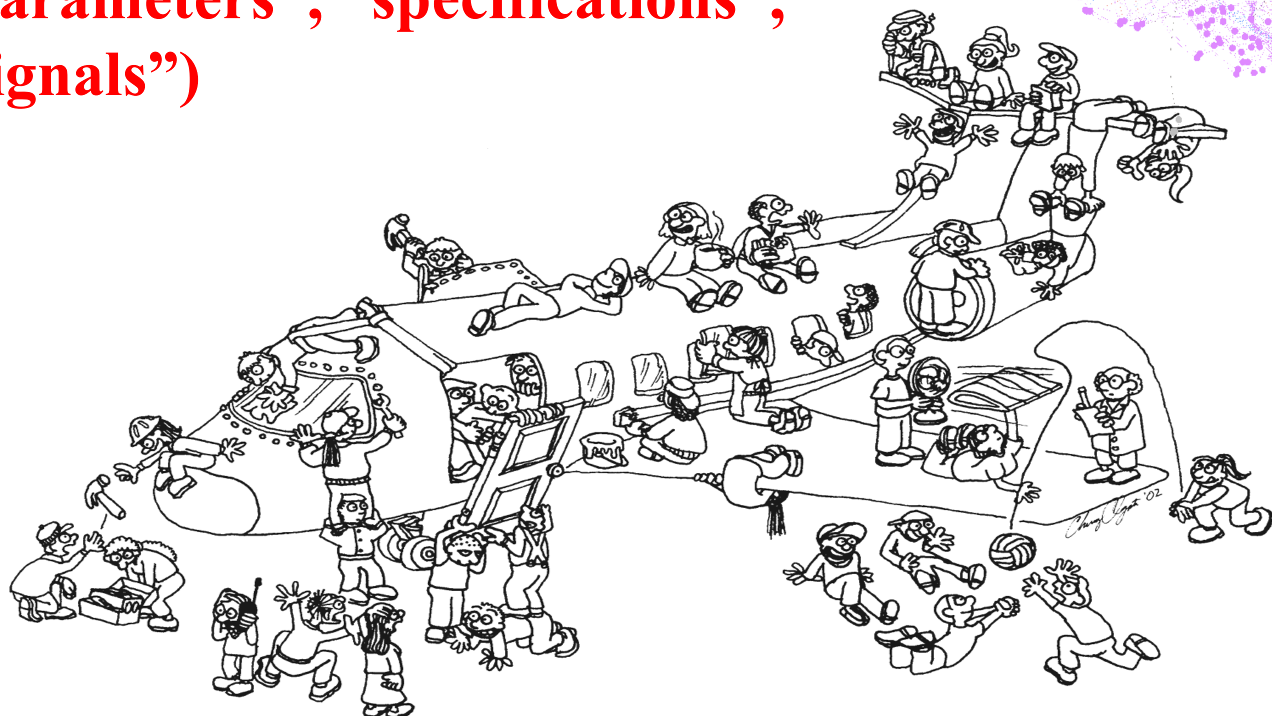
engineering nodes

(“people,” “tasks,” “components,” “subroutines”, “logic gates”)

connected by

information flows

(“engineering change orders”, “parameters”, “specifications”, “signals”)



The Laws of Complex Design Networks

Sparseness: Small fraction of the possible number of links

Small World: High clustering with short average path lengths

Heavy-tailed Distributions : Many small nodes held together by a few hubs

Asymmetric Information Flows: incoming capacities of nodes are much more limited than outgoing capacities

Structure-based Dynamics: Spread is determined by network structure

Robustness and Fragility: Dynamics is ultra error tolerant, yet highly vulnerable to targeted perturbations

Sensitivity and Leverage: focusing engineering efforts on central nodes

Building Blocks: key design circuit elements evolved to perform similar tasks

Nested Modularity: Groups form a hierarchical structure

Sparseness

Complex Design Networks

Networks have only a small fraction of the possible number of links

	Network	Type	# Nodes	# Links
Open-Source Software	Linux-kernel	Directed	5,420	11,460
	MySQL	Directed	1,501	4,245
Forward Logic Chip	s38417 electronic circuit	Directed	23,843	33,661
	s38584 electronic circuit	Directed	20,717	34,204
Product Development	Vehicle	Directed	120	417
	Pharma facility	Directed	582	4,123
	16 story hospital	Directed	889	8,178

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Complex Design Networks

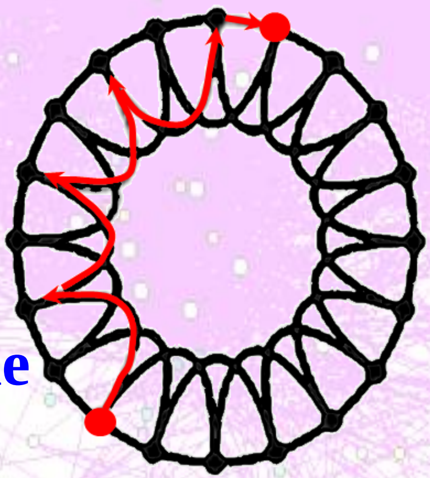
Small World

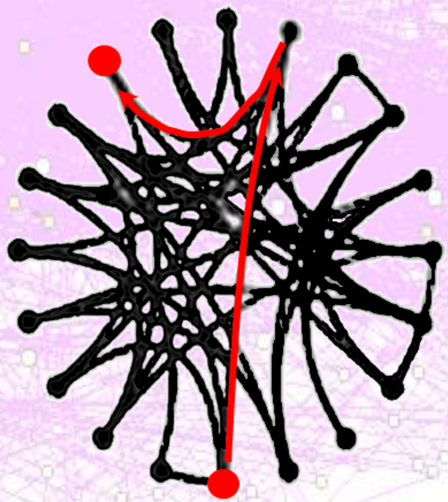
Networks are clustered but have a small characteristic path length

Crystal? **Random?**

High Modularity

High node-to-node distance





Low Modularity

Low node-to-node distance

Small World Complex Design Networks

Networks are clustered but have a small characteristic path length

	Network	d	d_{rand}	C	C_{rand}
Open-Source Software	Linux-kernel	4.66	5.87	0.14	0.001
	MySQL	5.47	4.20	0.21	0.004
Product Development	Vehicle	2.88	2.73	0.21	0.05
	Pharma facility	2.63	2.77	0.45	0.02
	16 story hospital	3.12	2.58	0.27	0.02
	Microprocessor	2.09	2.40	0.415	0.1466
	Equipment	3.21	2.60	0.50	0.10

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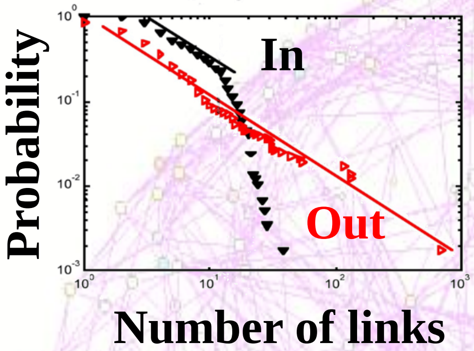
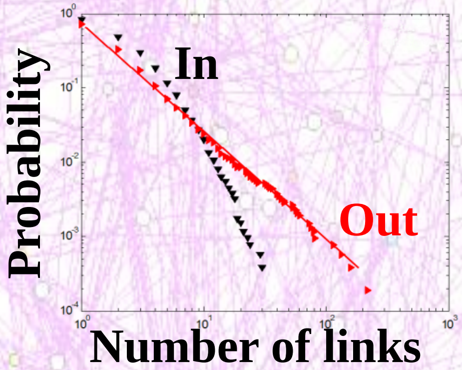
Complex Design Networks

Pharmaceutical facility



Linux-kernel



Heavy-tailed Distributions

Right-skewed and fat-tailed in-degree and out-degree distributions

Information Bottlenecks (“Design Hubs”)

“Receivers,” “Generators” & “Brokers”

Asymmetric Information Flows

incoming capacities of nodes are much more limited than outgoing capacities

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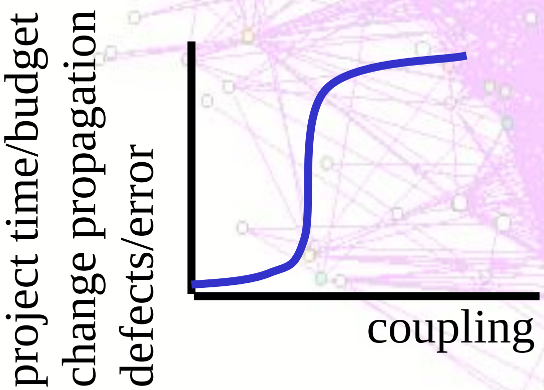
Complex Design Networks

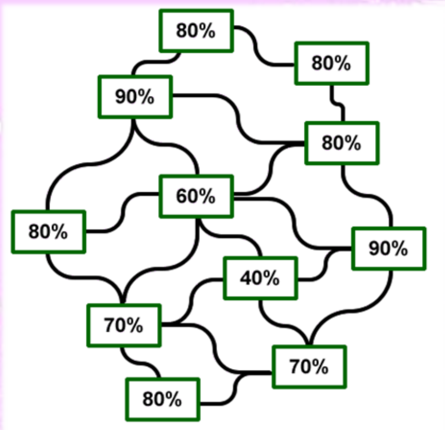
Structure-based Dynamics

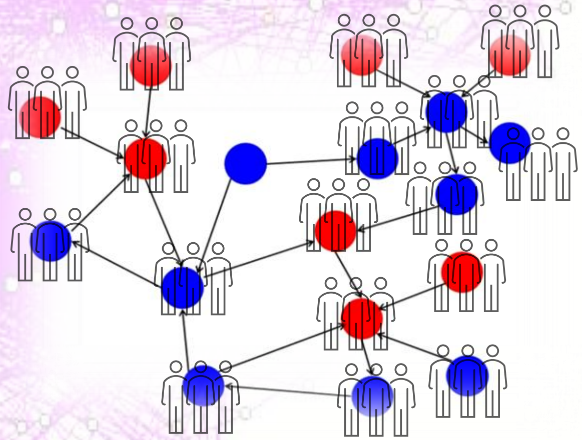
Design Network structure provides direct information about its dynamics (behavior)

Design dynamics is controlled by the extent of coupling and correlations in the network

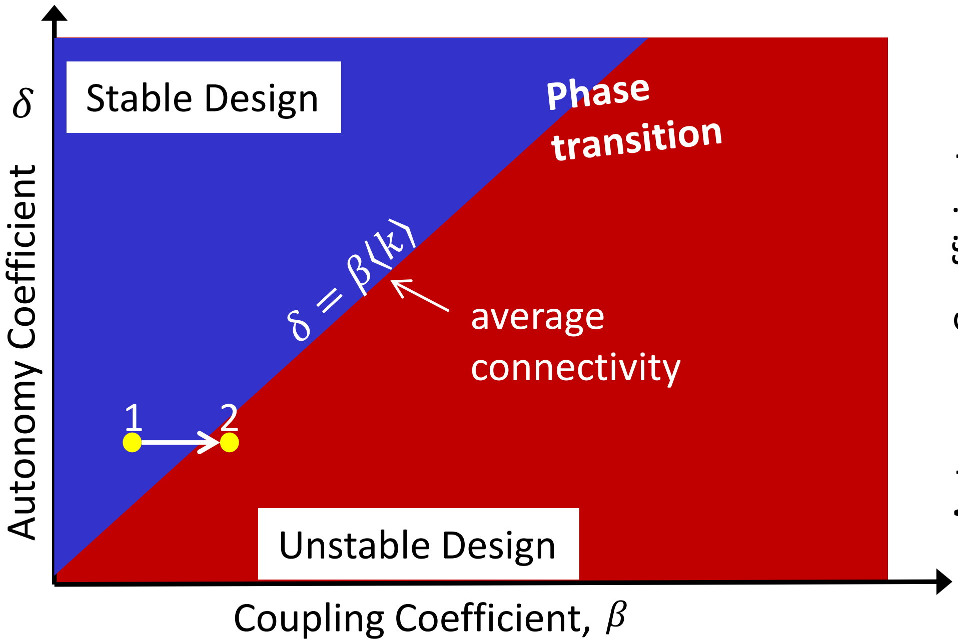
Phase transitions

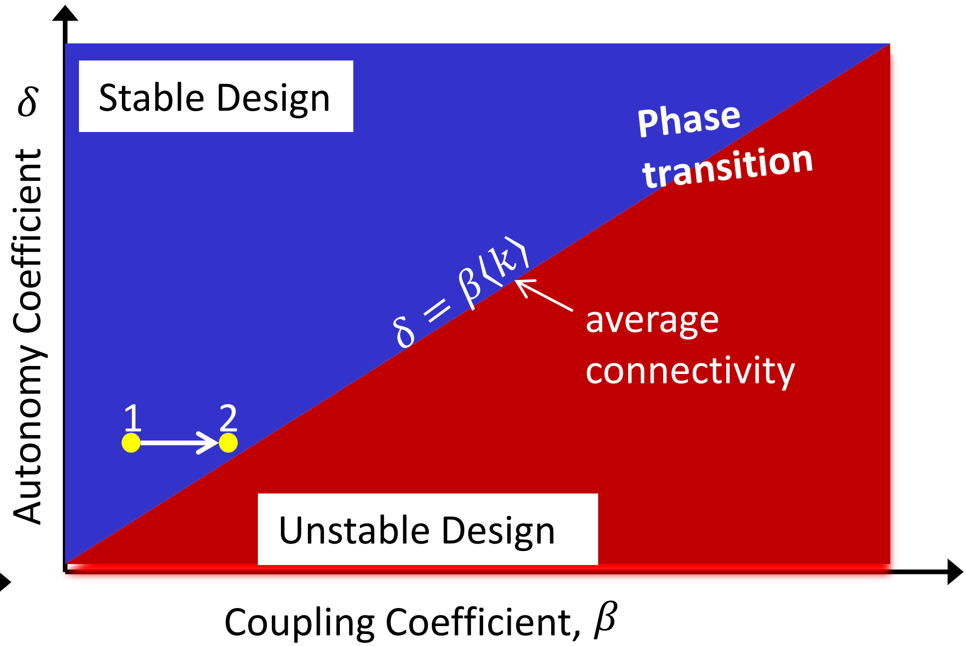




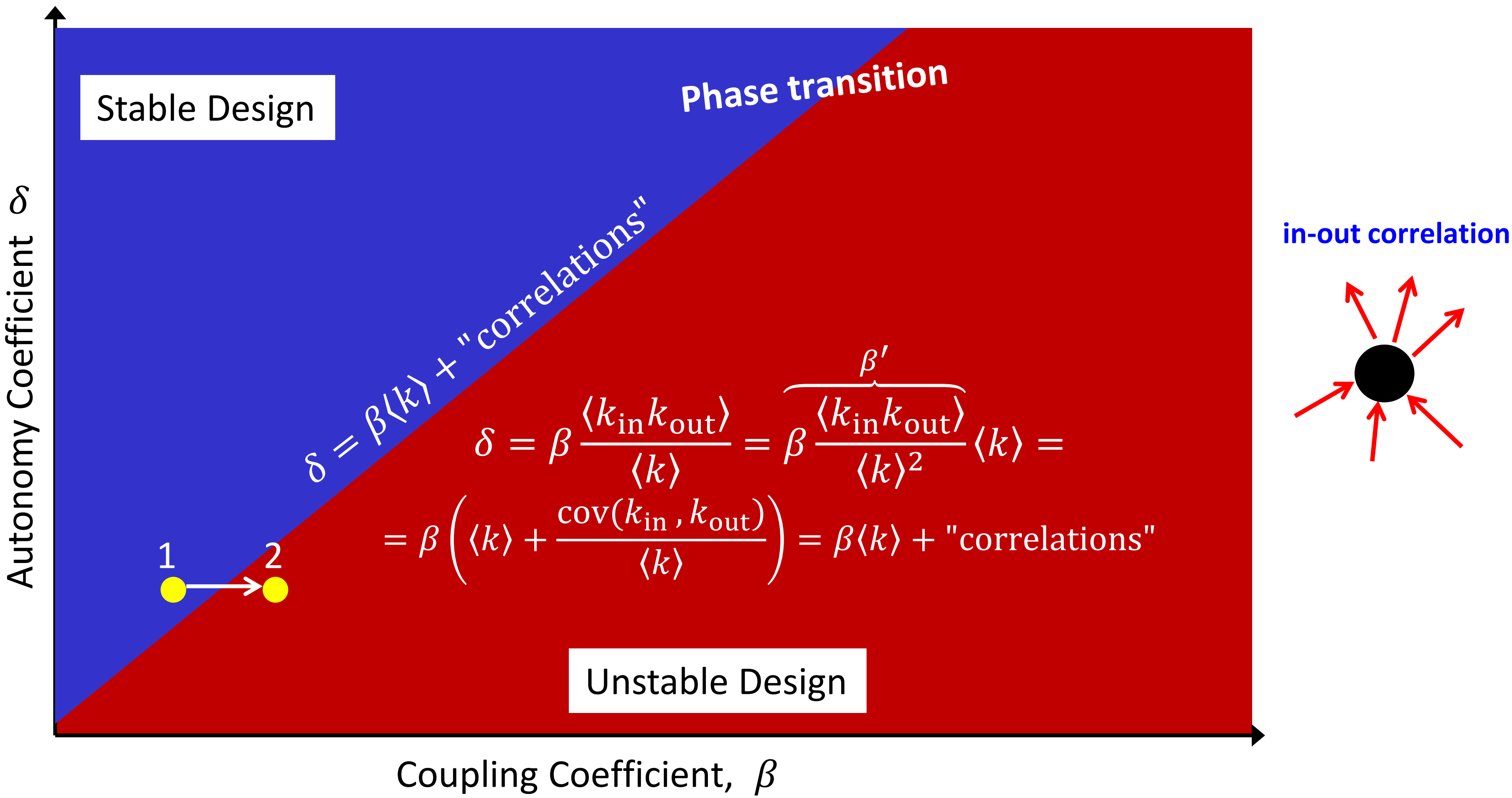


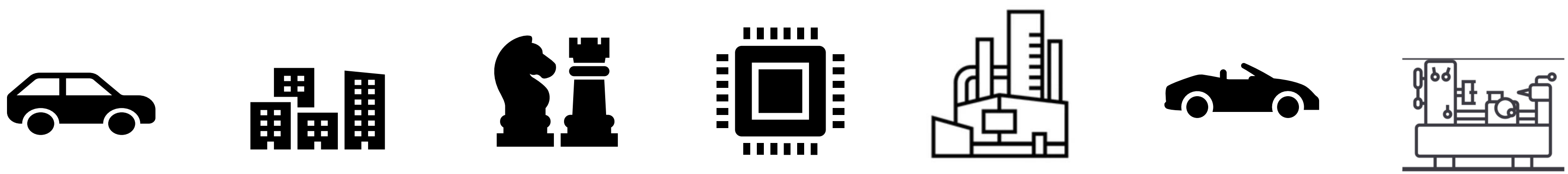
Error/Change Propagation in Complex Design Networks (Random Network)





Error/Change Propagation on Complex Design Networks (Real Design Networks)





0.172 **0.232*** **-0.185** **0.003** **-0.33*** **-0.016** **0.258**

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Building Blocks: key design circuit elements evolved to perform similar tasks

Nested Modularity: Groups form a hierarchical structure

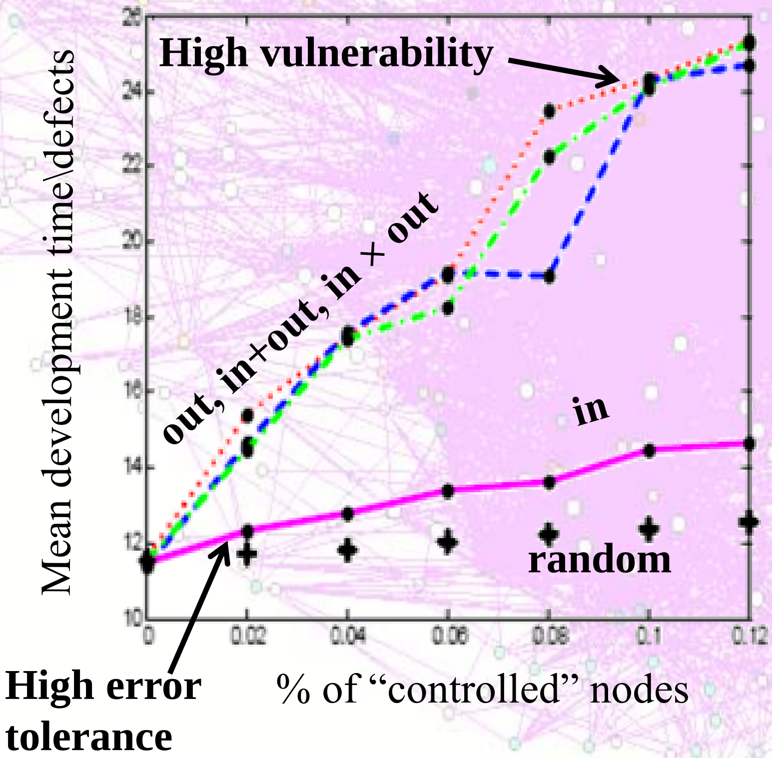
Complex Design Networks

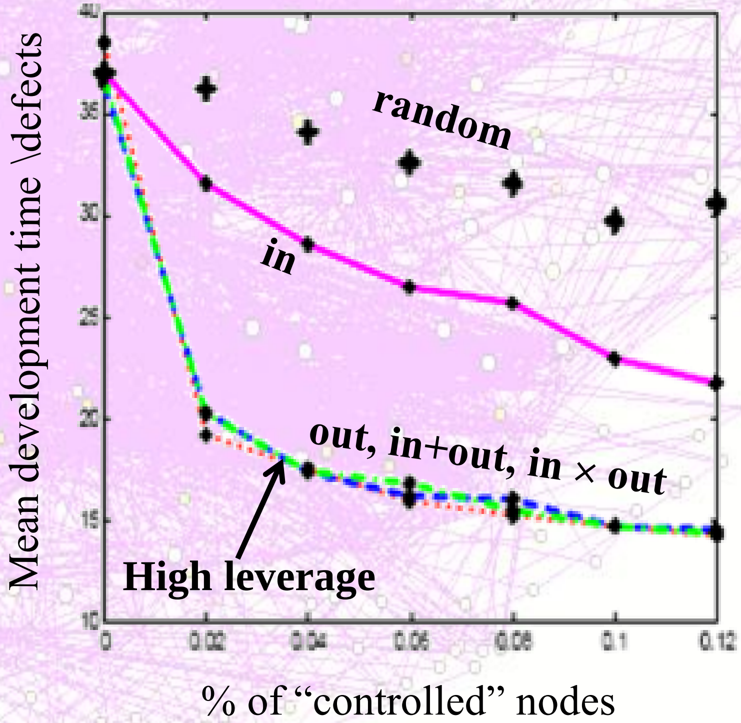
Robustness and Fragility

Dynamics is ultra error tolerant, yet highly vulnerable to "perturbations" targeted at central nodes

Sensitivity and Leverage

Preferential design policy of focusing engineering efforts on central nodes





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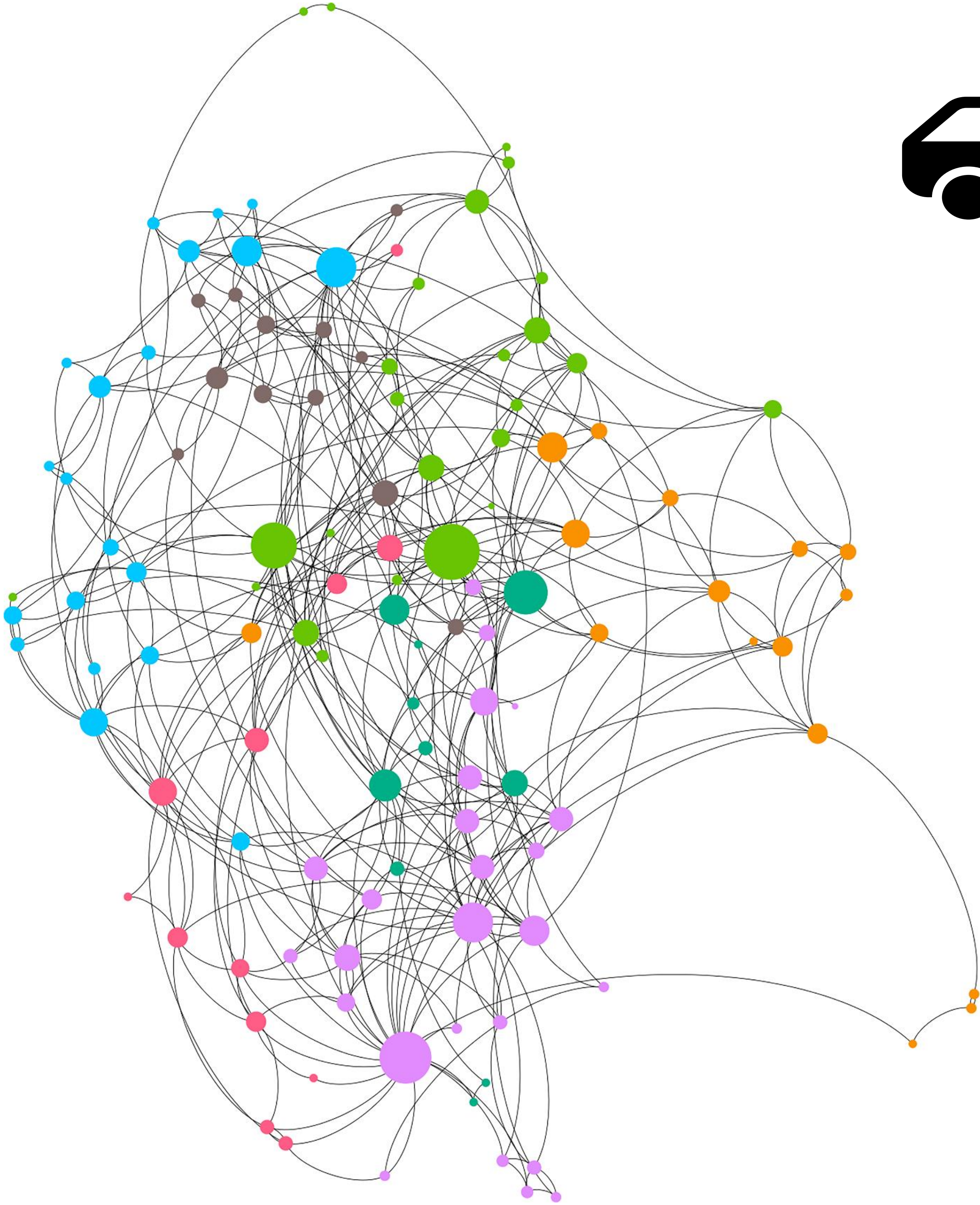
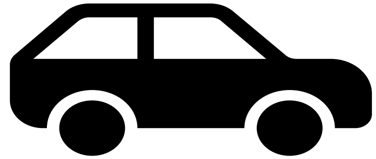
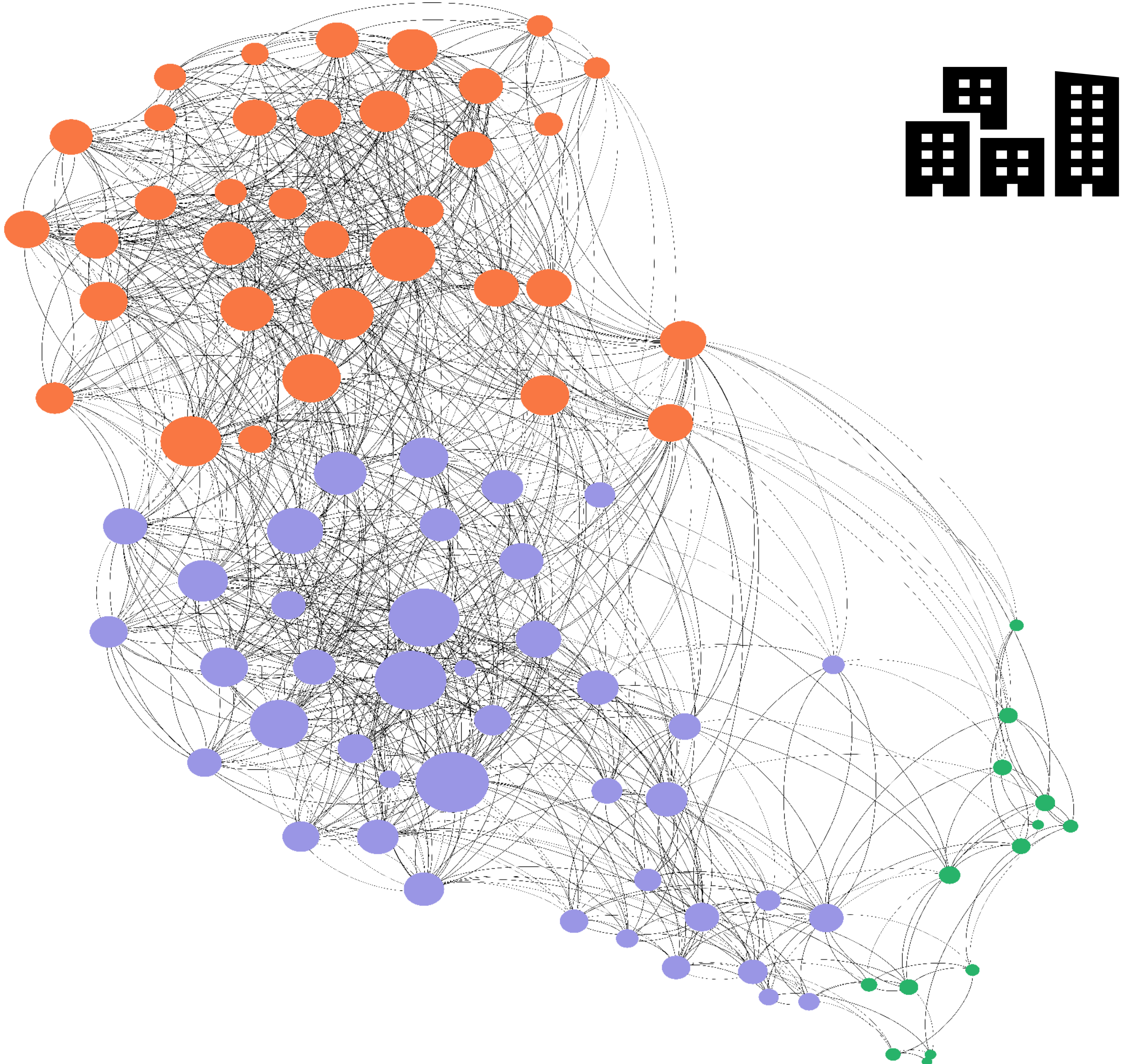
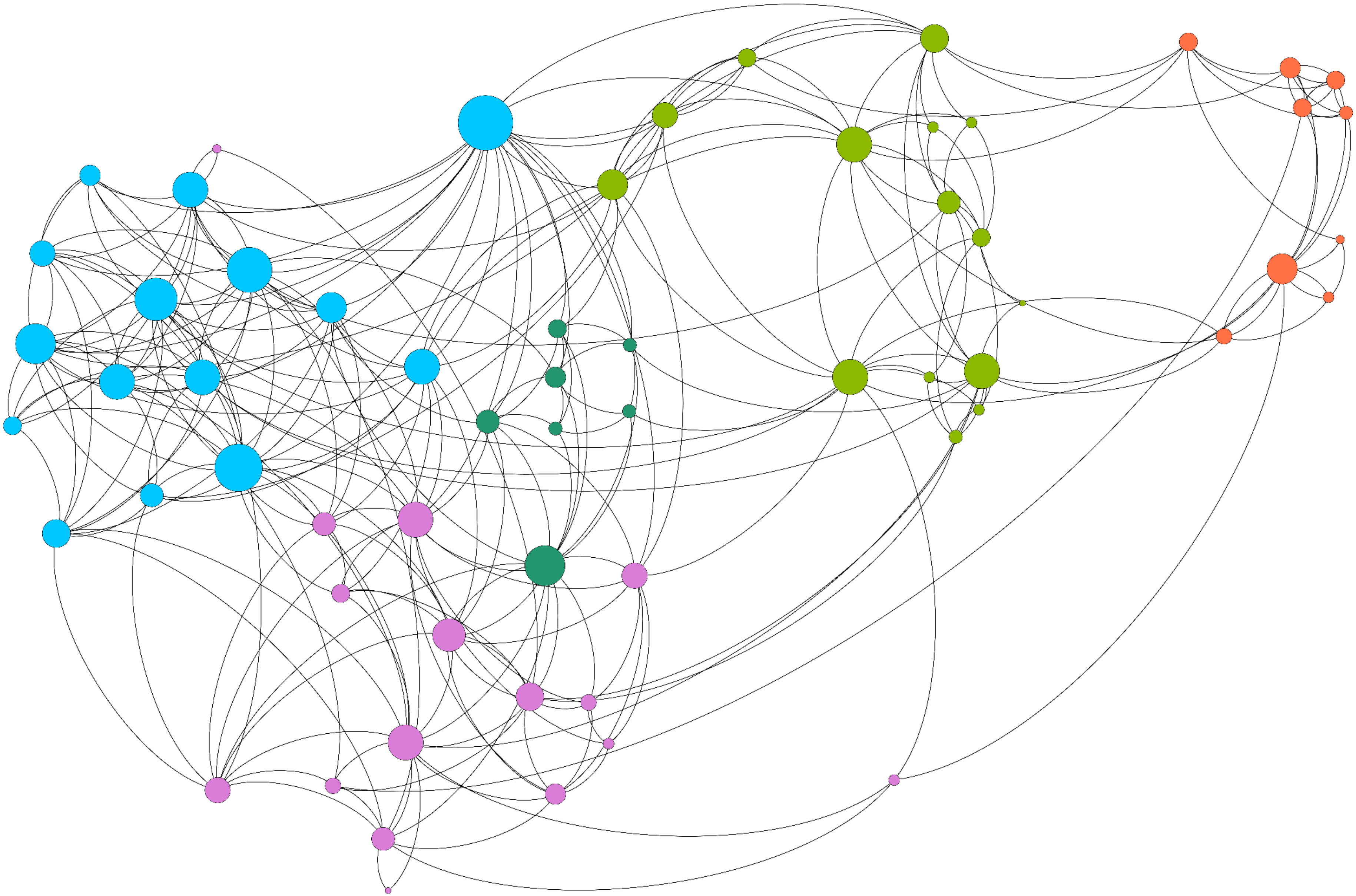
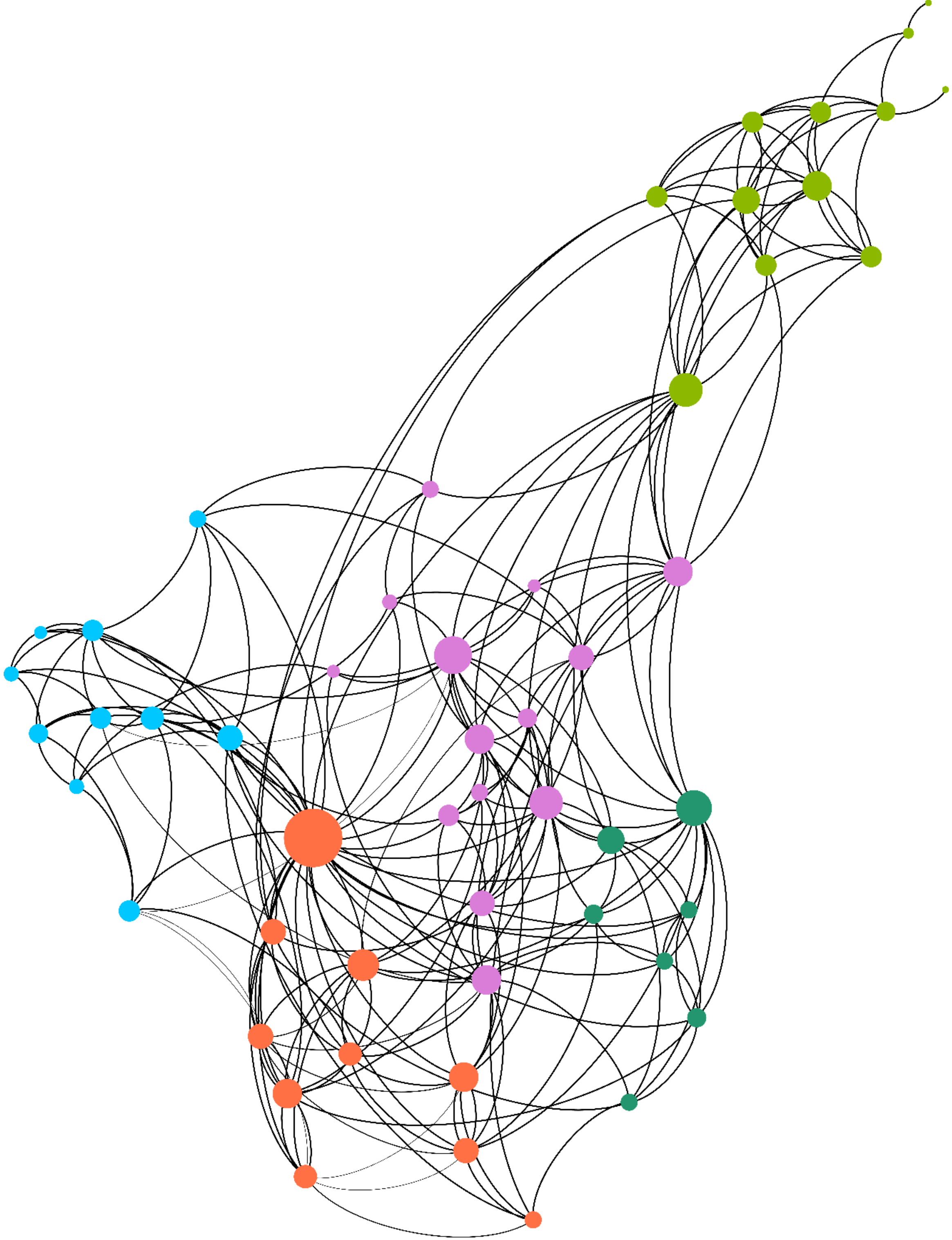
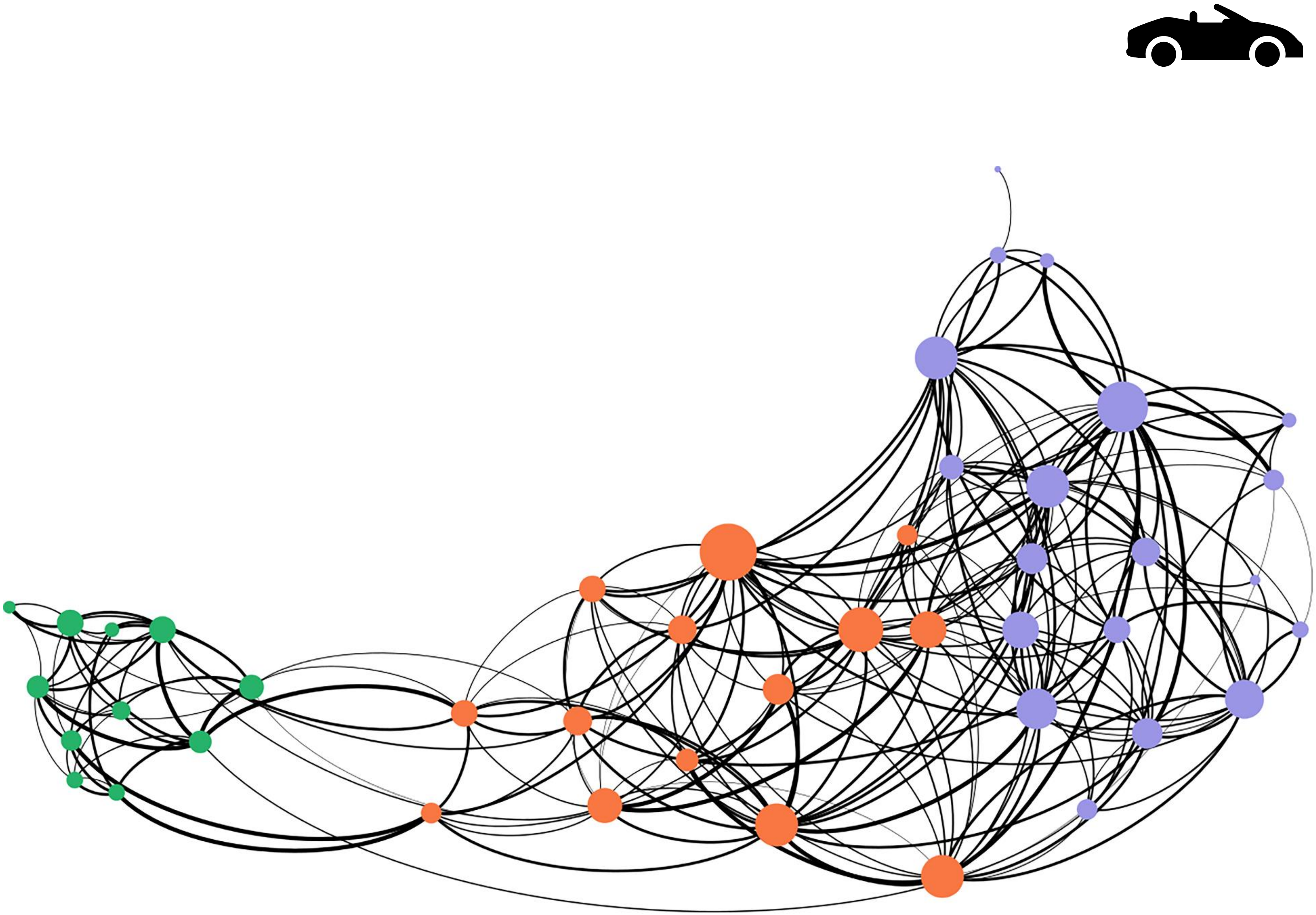


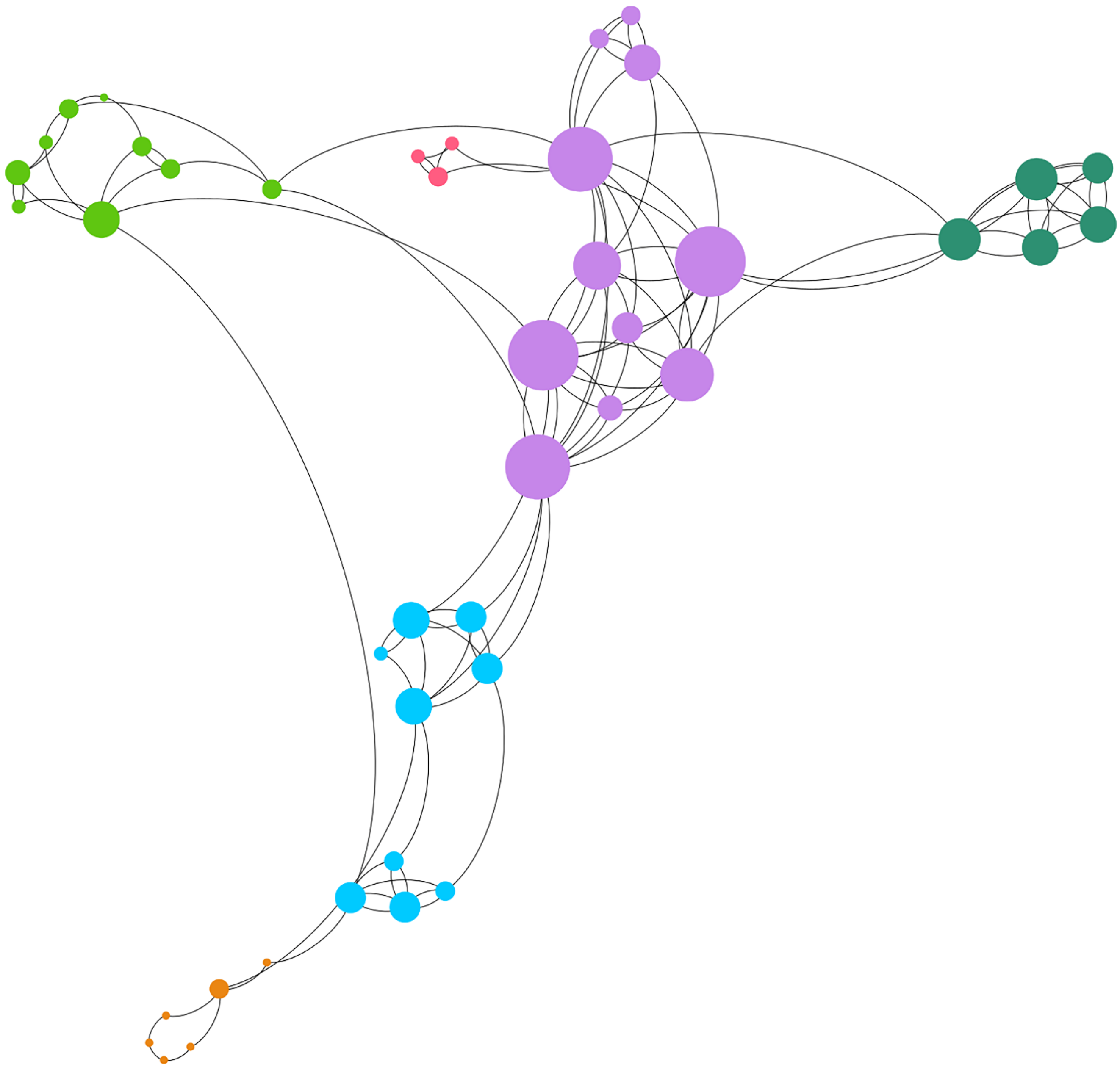




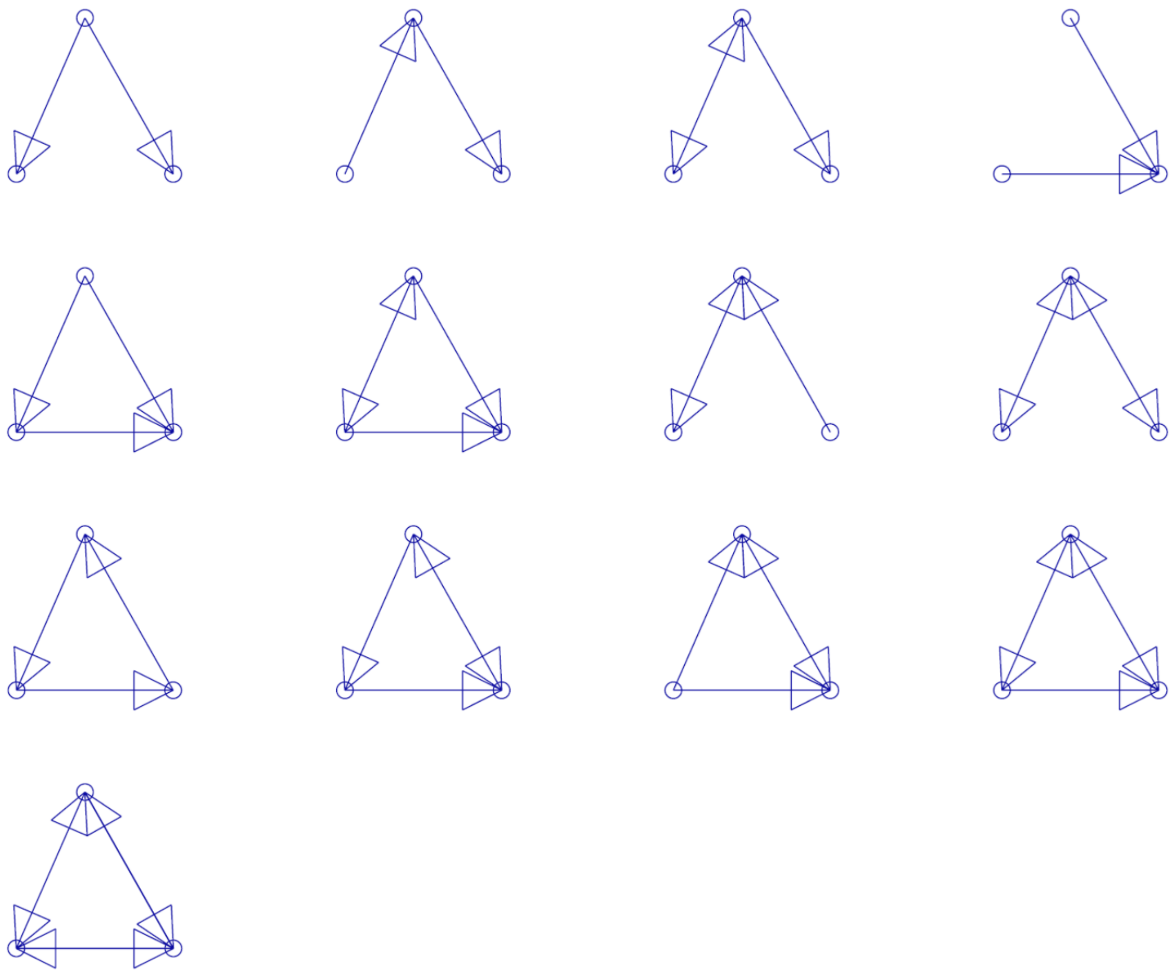




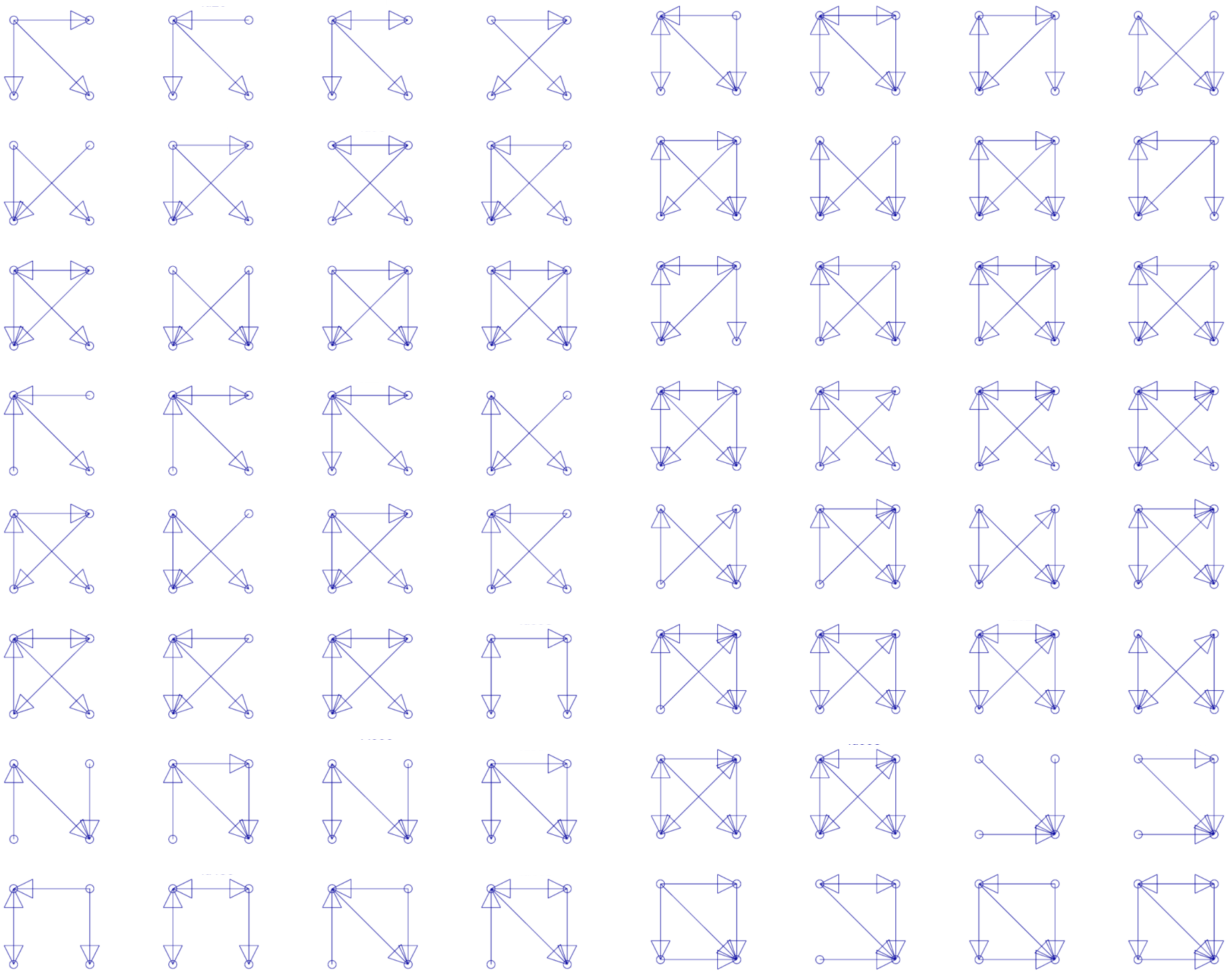




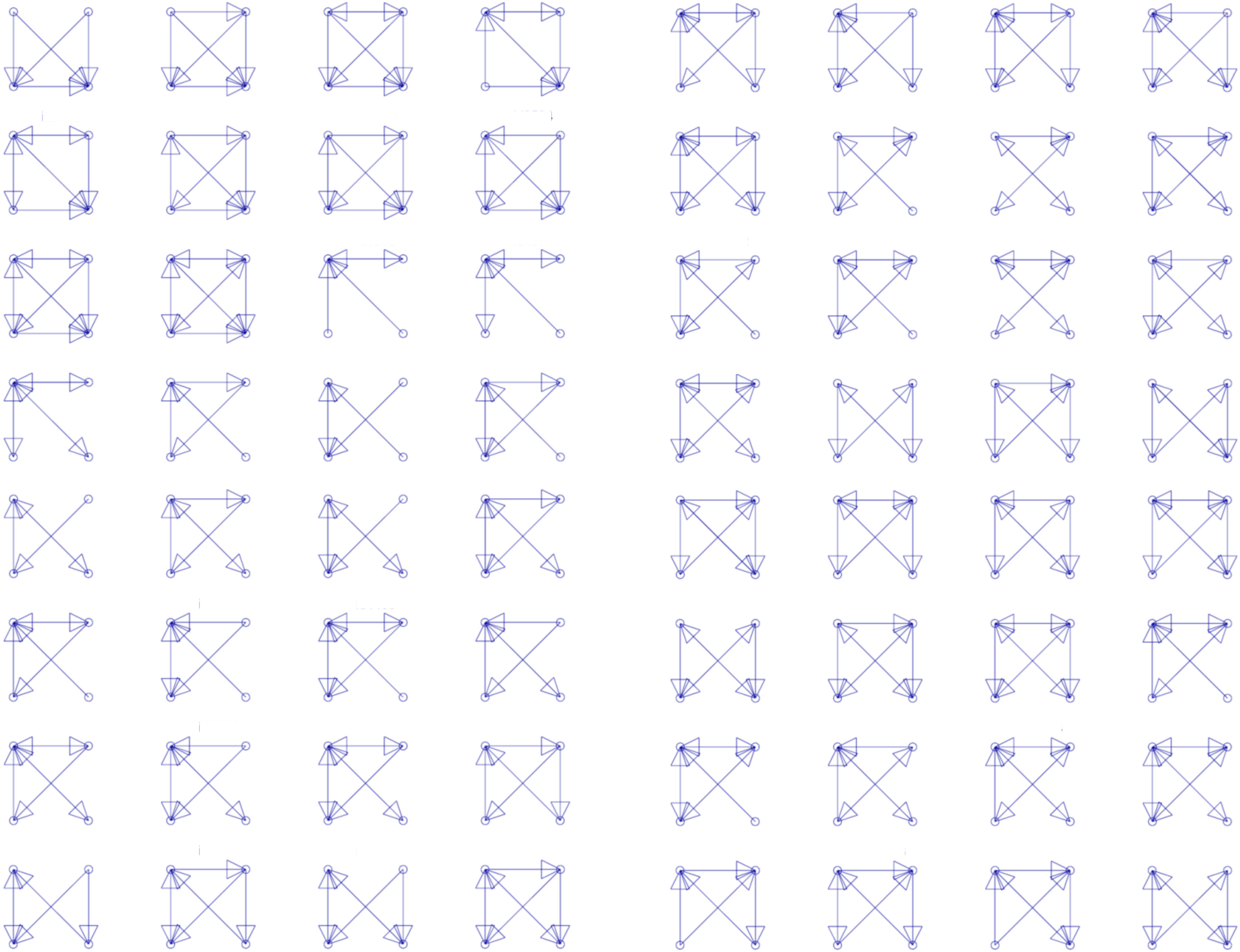
3-Node Subgraphs



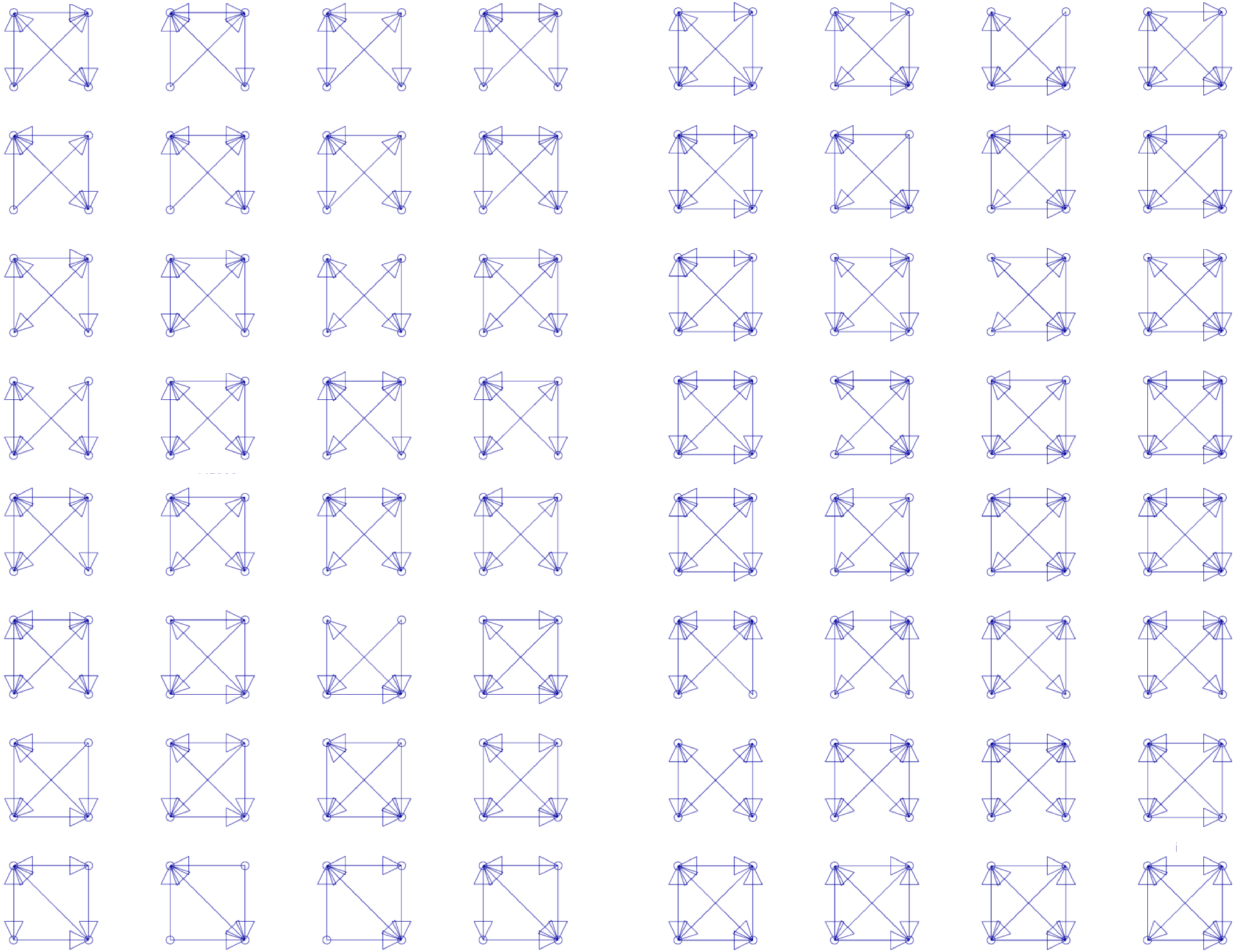
4-Node Subgraphs



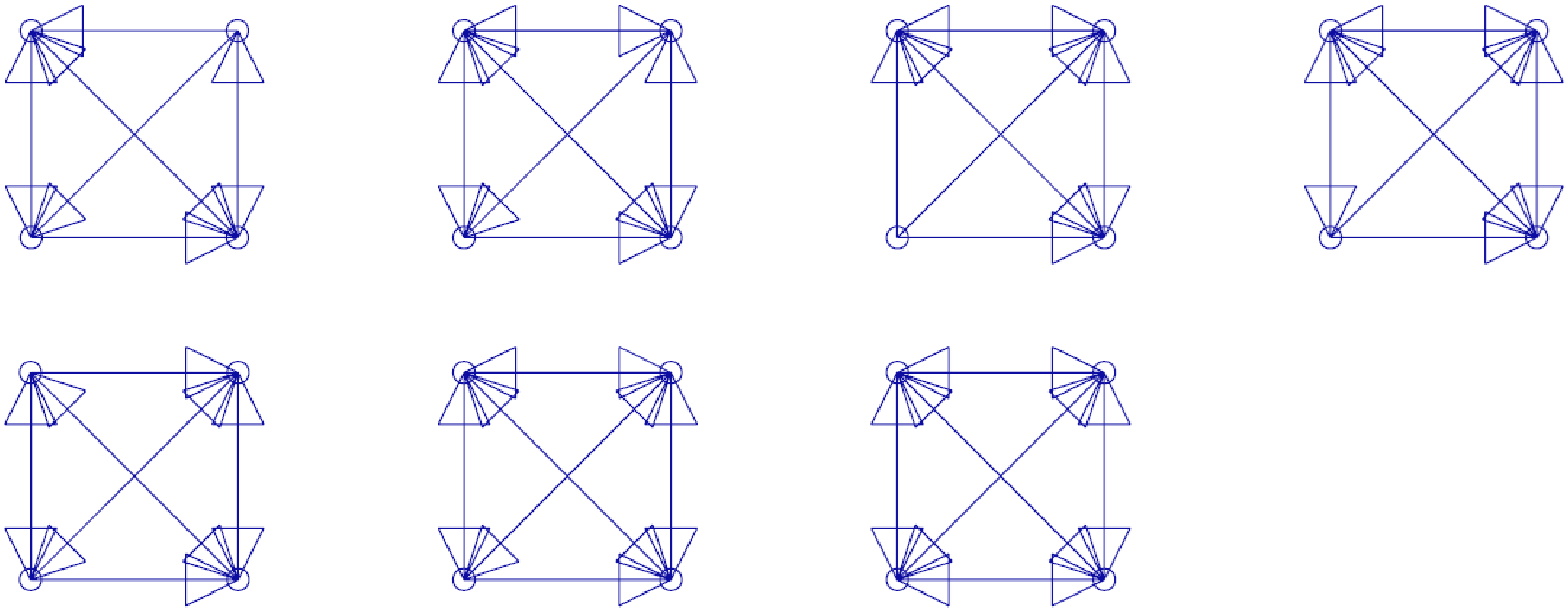
4-Node Subgraphs



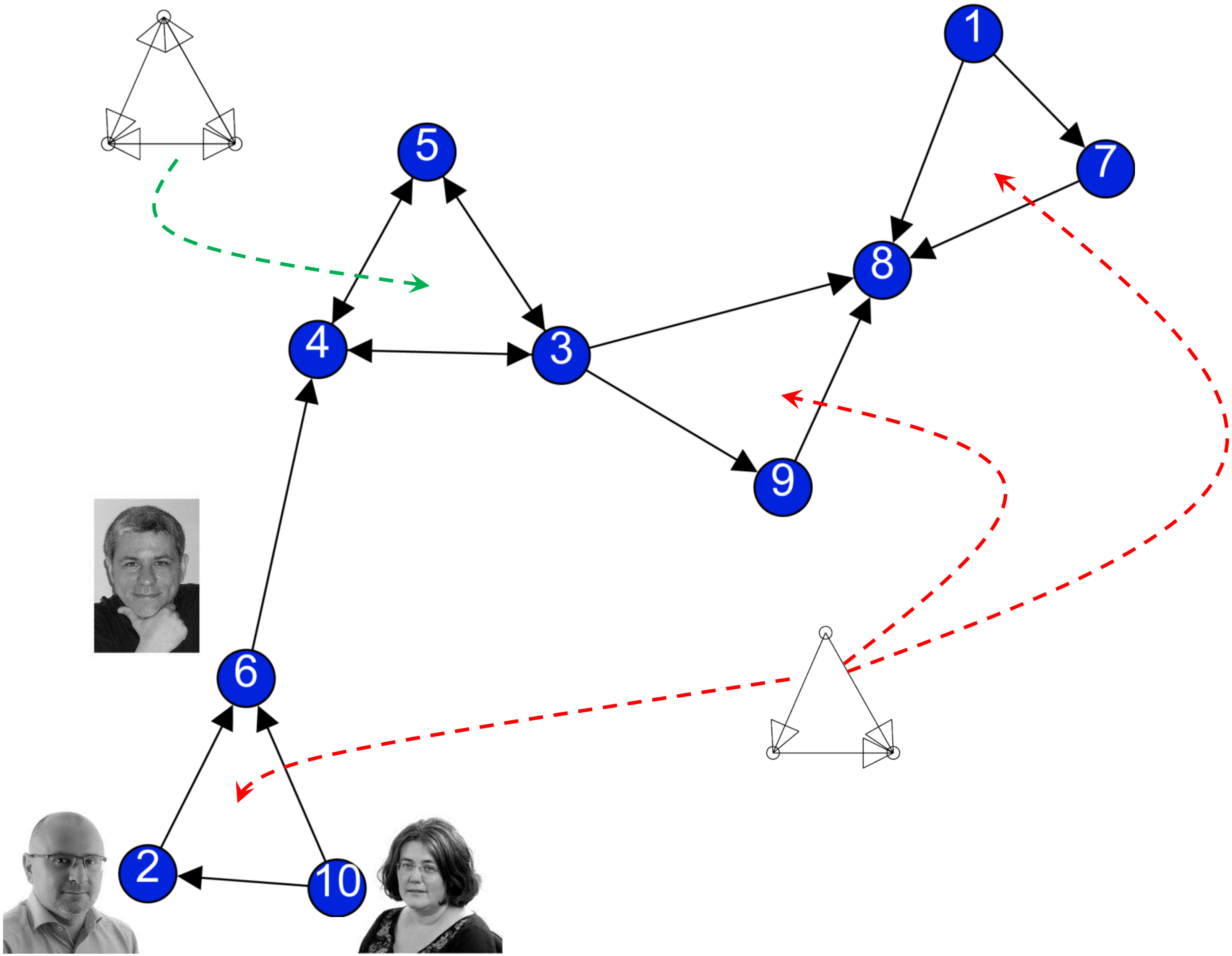
4-Node Subgraphs



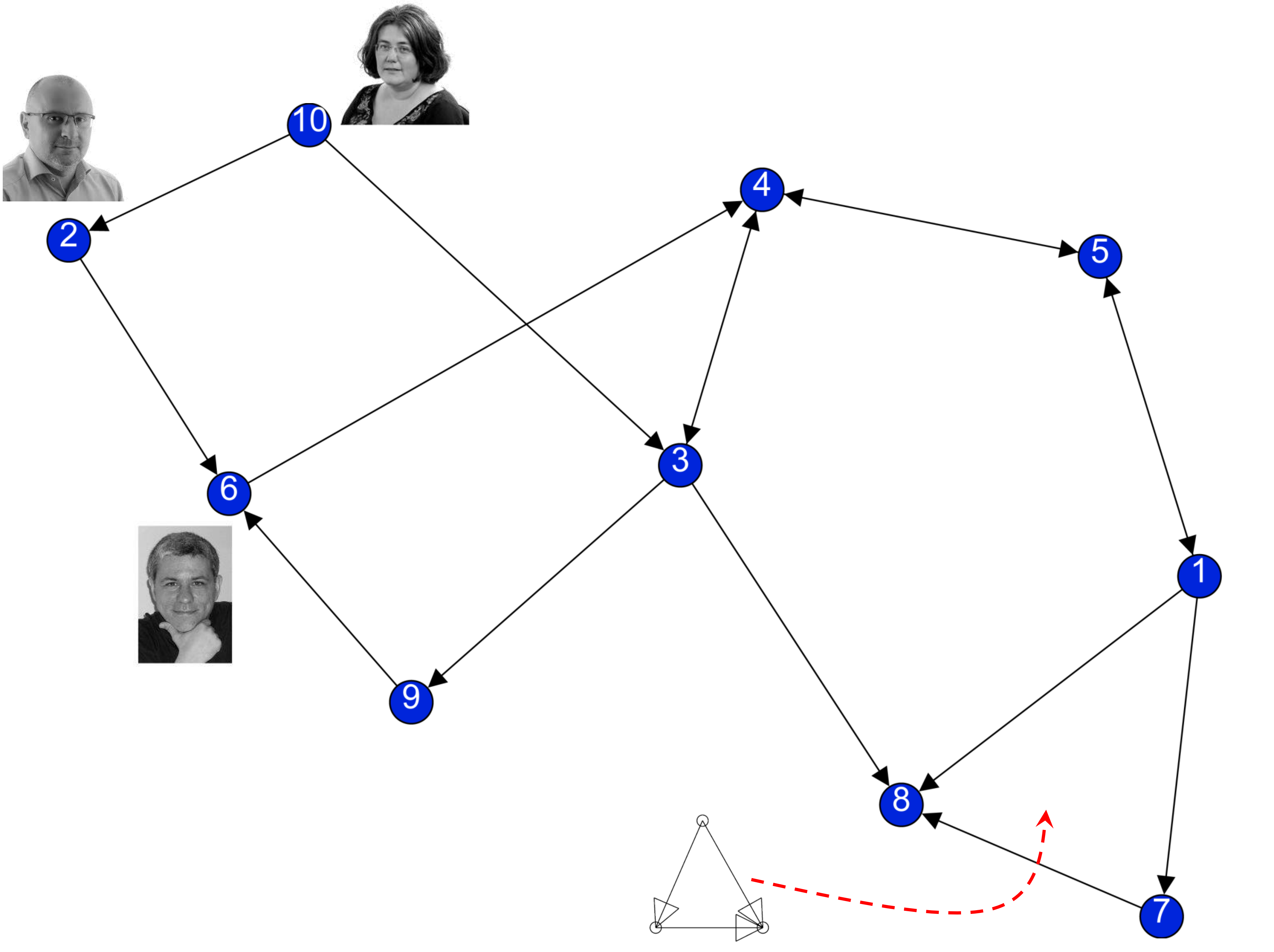
4-Node Subgraphs



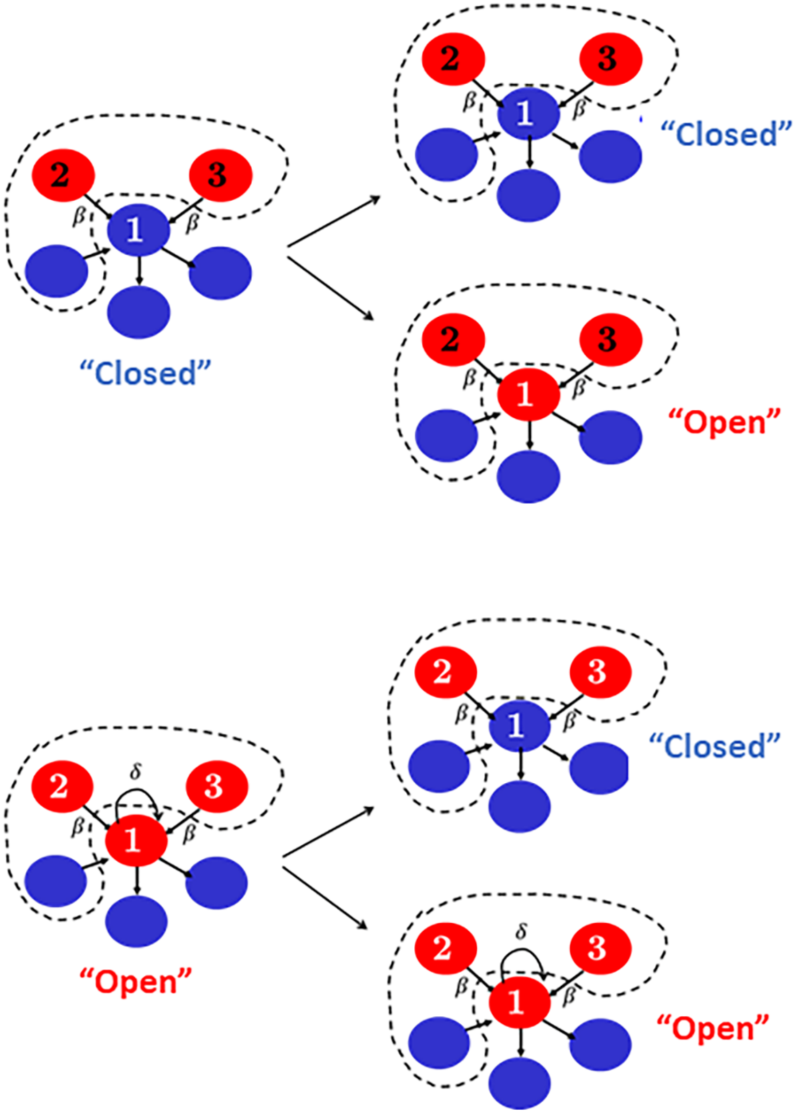
“Real-World” Design Network

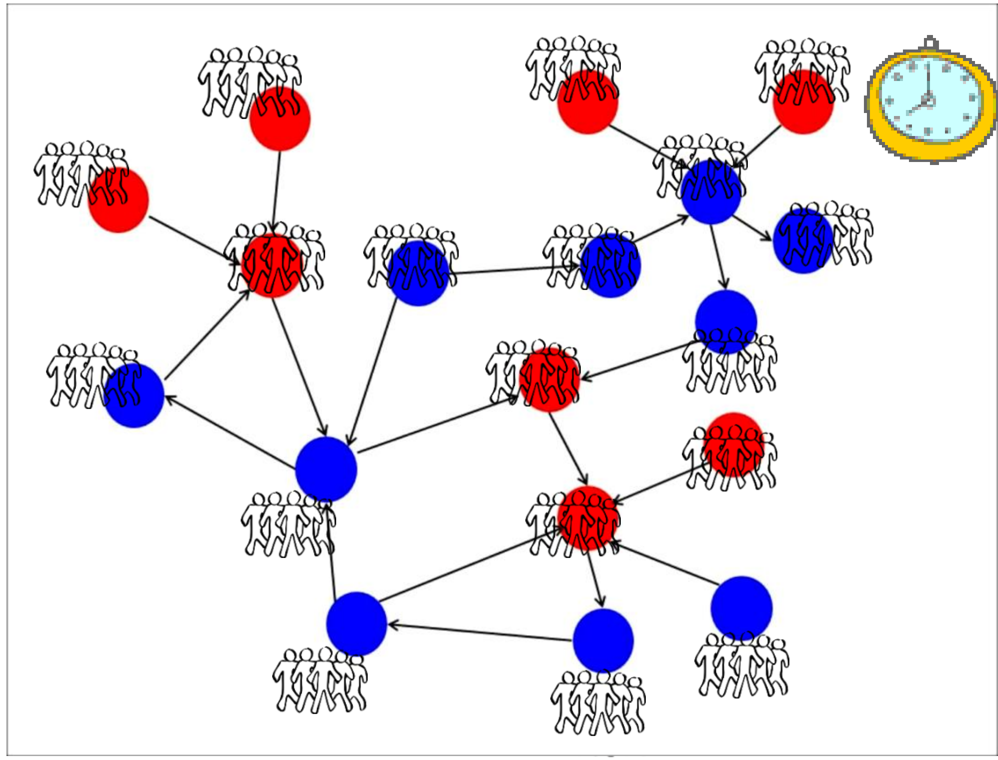


“Randomized” Design Network



A Dynamic Network Model of Error/Change Propagation on Complex Design Networks

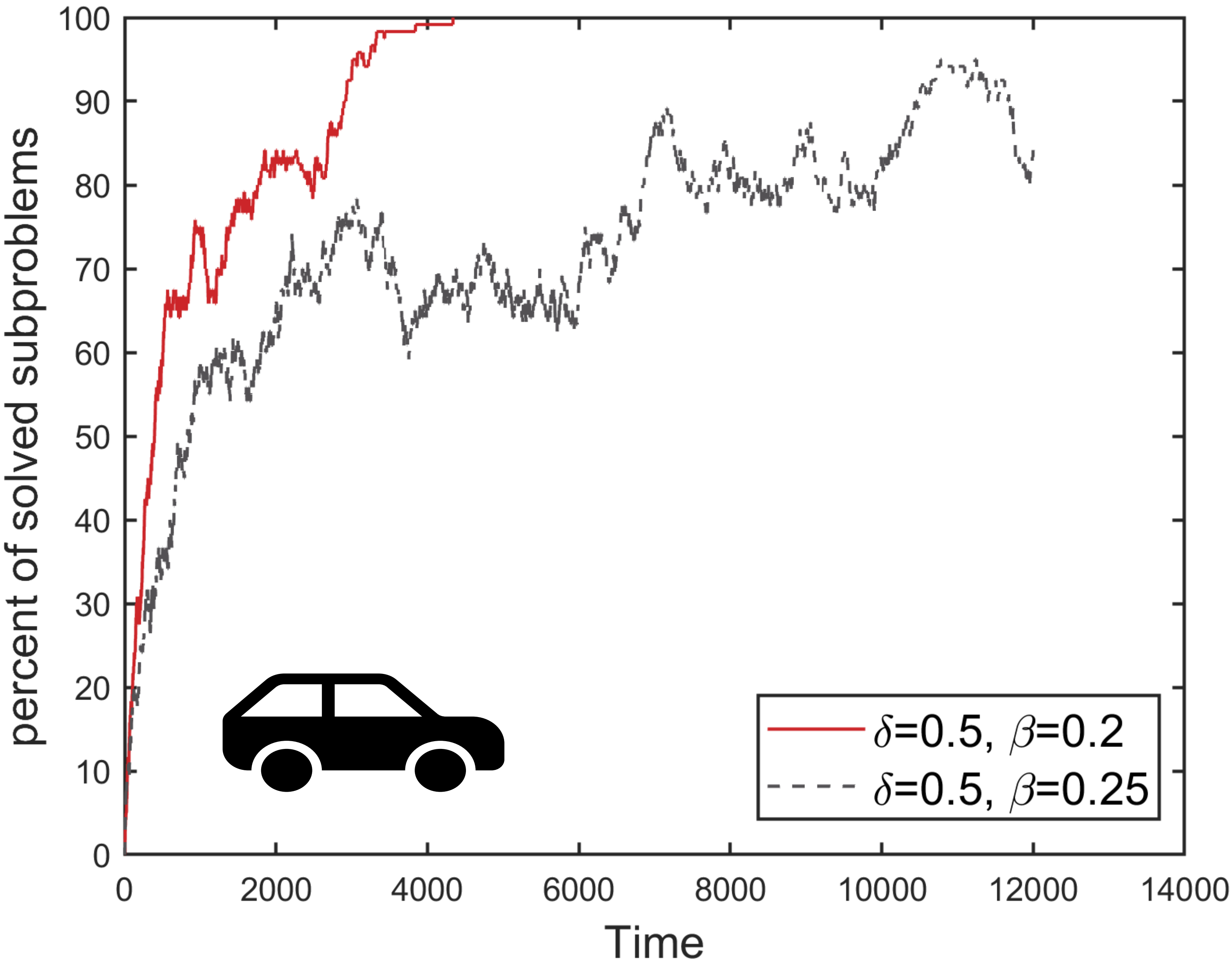




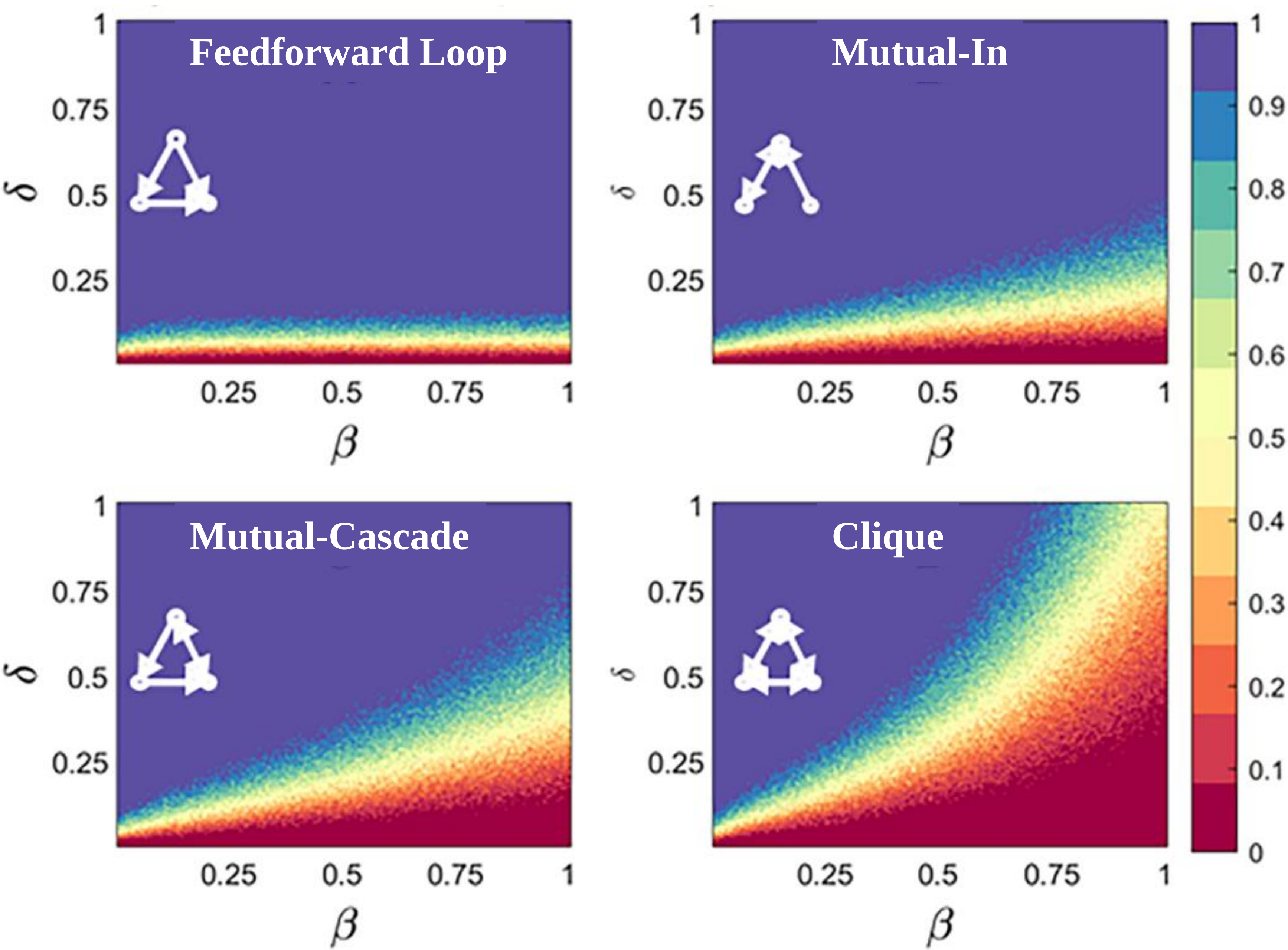
β – Interdependency parameter

δ – Autonomy parameter

Synchronization of Design Problem Solving Over Time

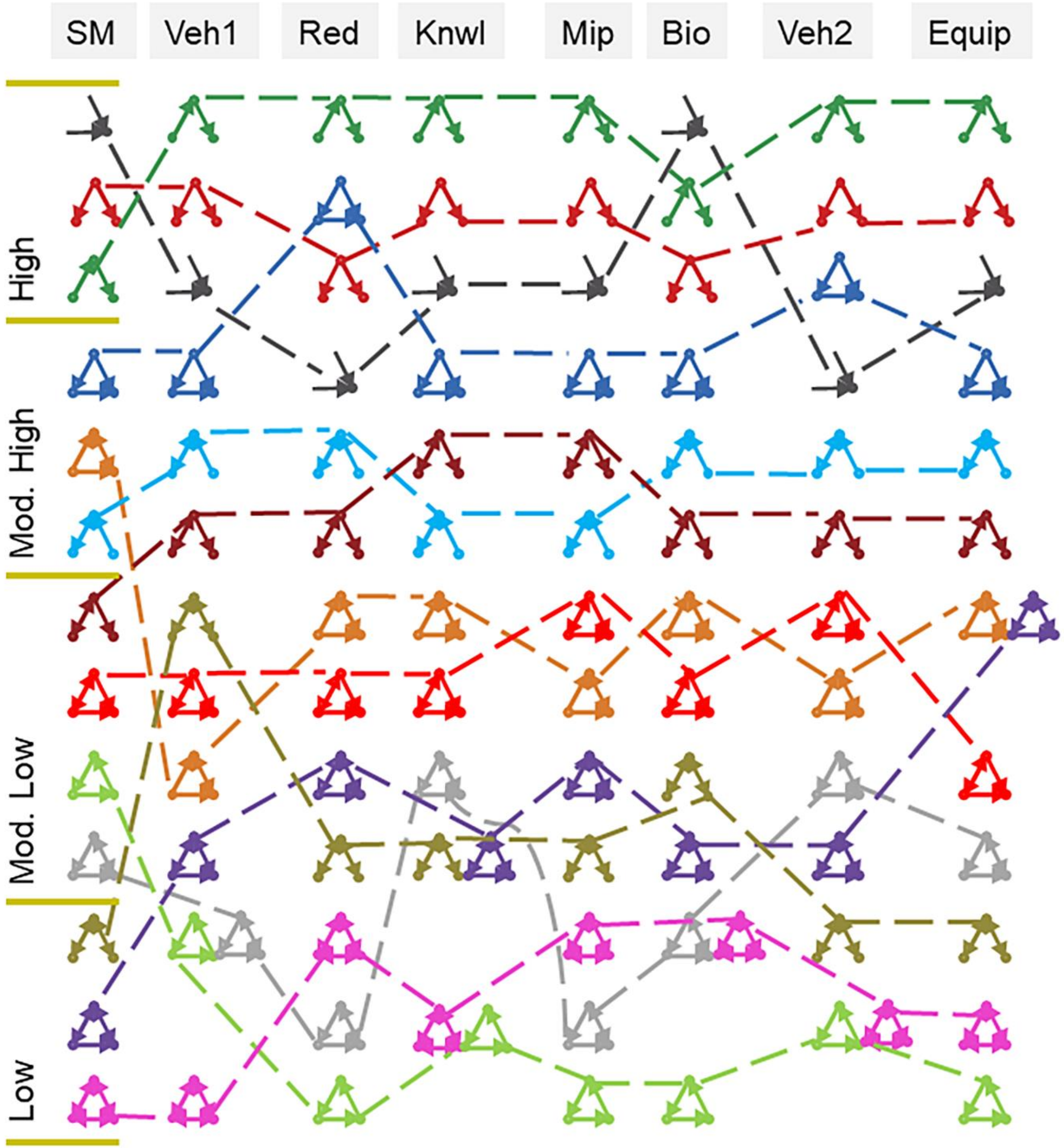


Synchronization Probability of 3-node Motifs



https://www.nature.com/articles/s41598-020-75221-3

Subgraph Ranking by Synchronizability Metric and Frequency



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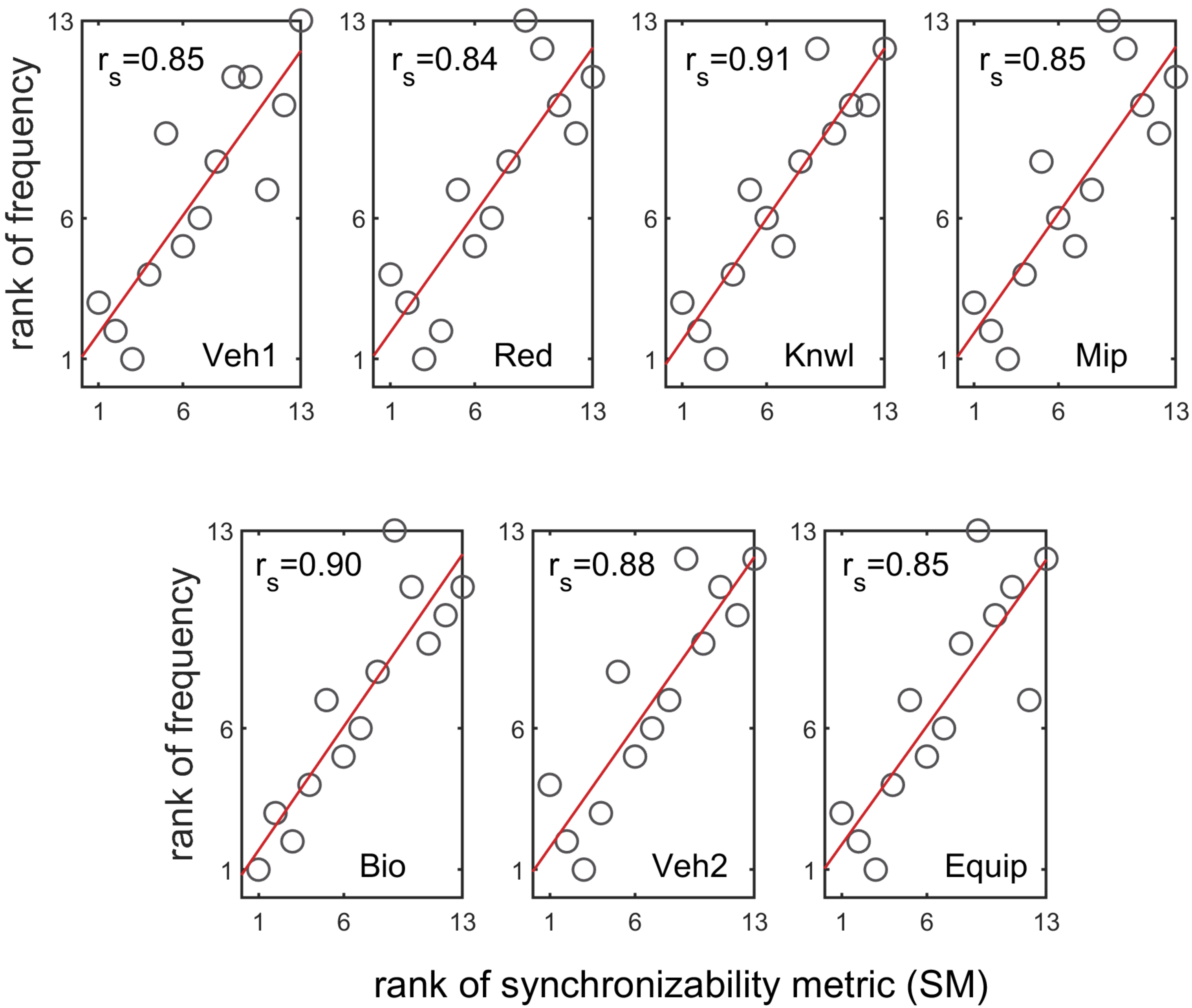
Spearman's Rank Correlations (3-Node Subgraphs)



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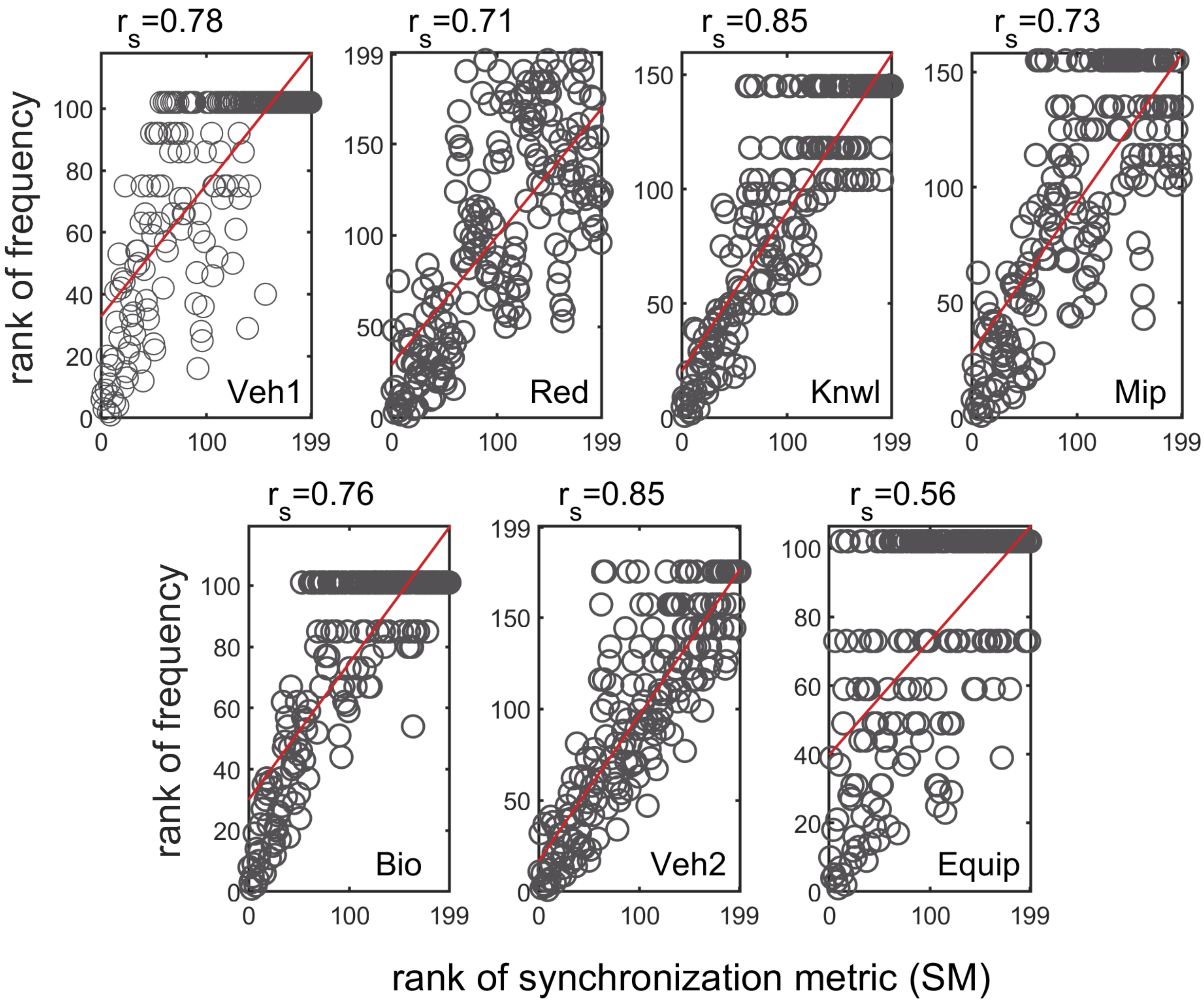
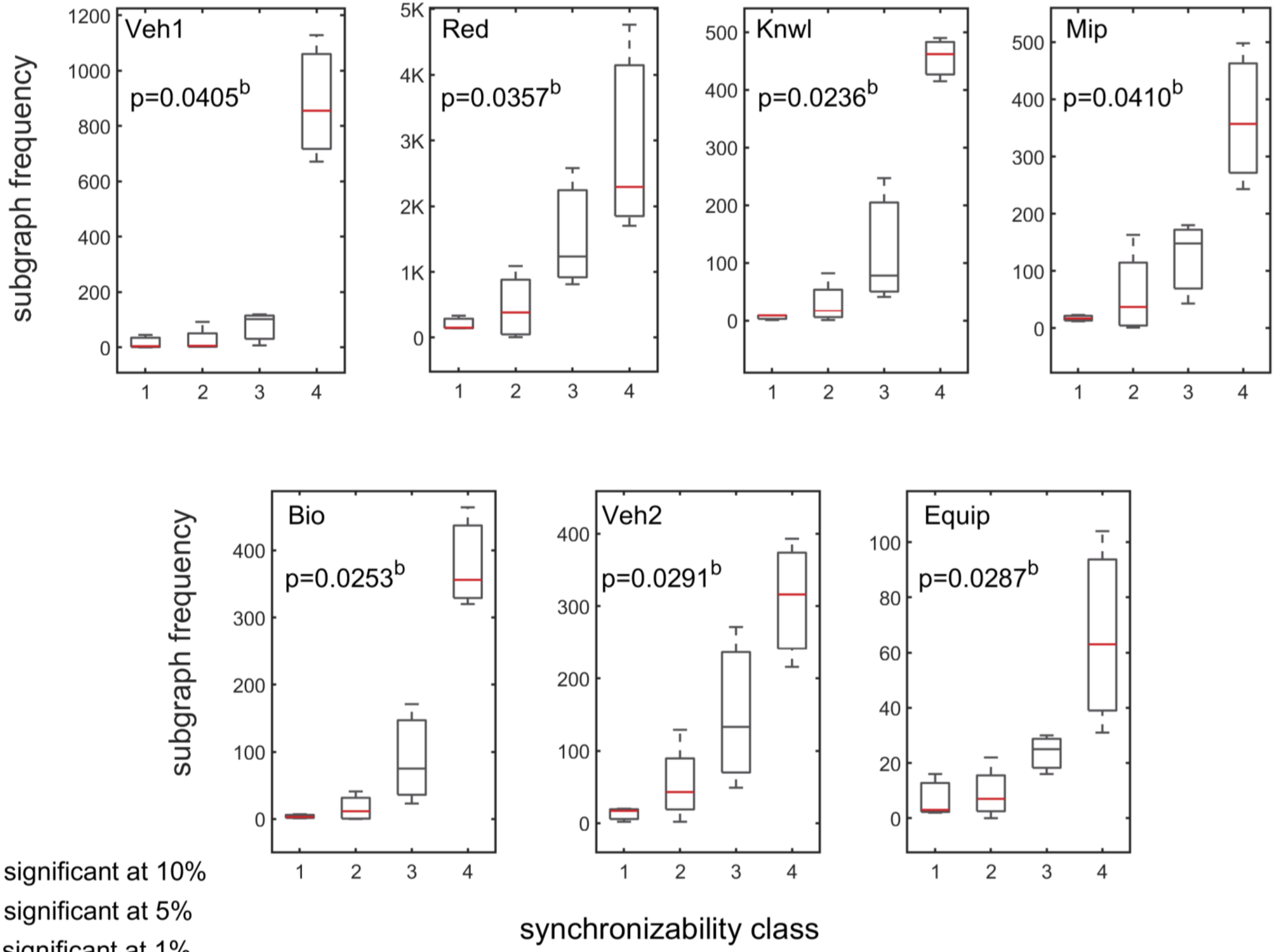
Spearman's Rank Correlations (4-Node Subgraphs)



https://www.nature.com/articles/s41598-020-75221-3

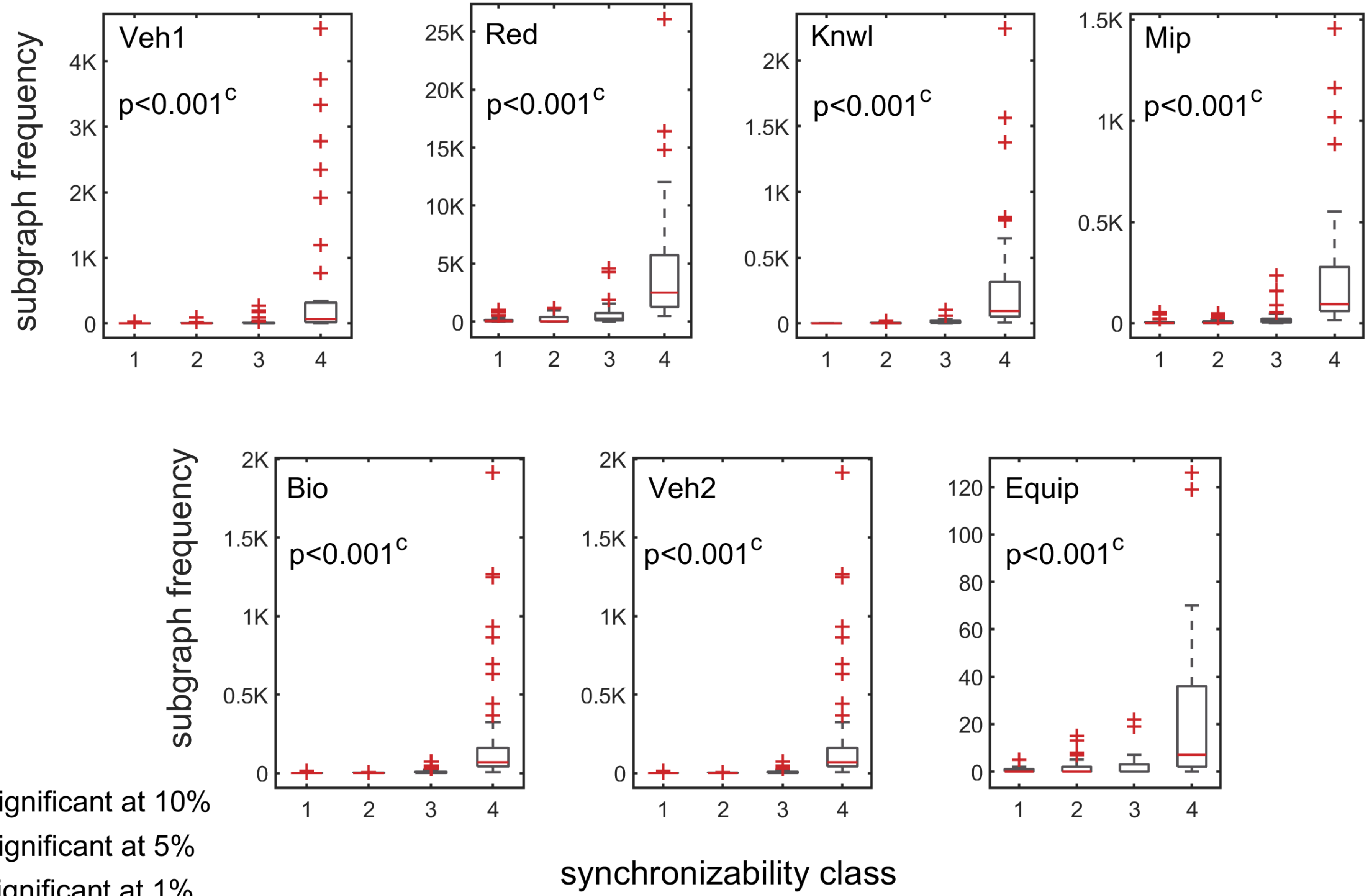
Subgraph Frequency Classified by Synchronizability Class (3-node Subgraphs)



[a] significant at 10%
[b] significant at 5%
[c] significant at 1%

https://www.nature.com/articles/s41598-020-75221-3

Subgraph Frequency Classified by Synchronizability Class (4-node Subgraphs)



[a] significant at 10%
[b] significant at 5%
[c] significant at 1%

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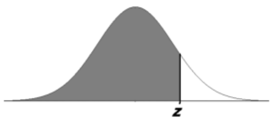
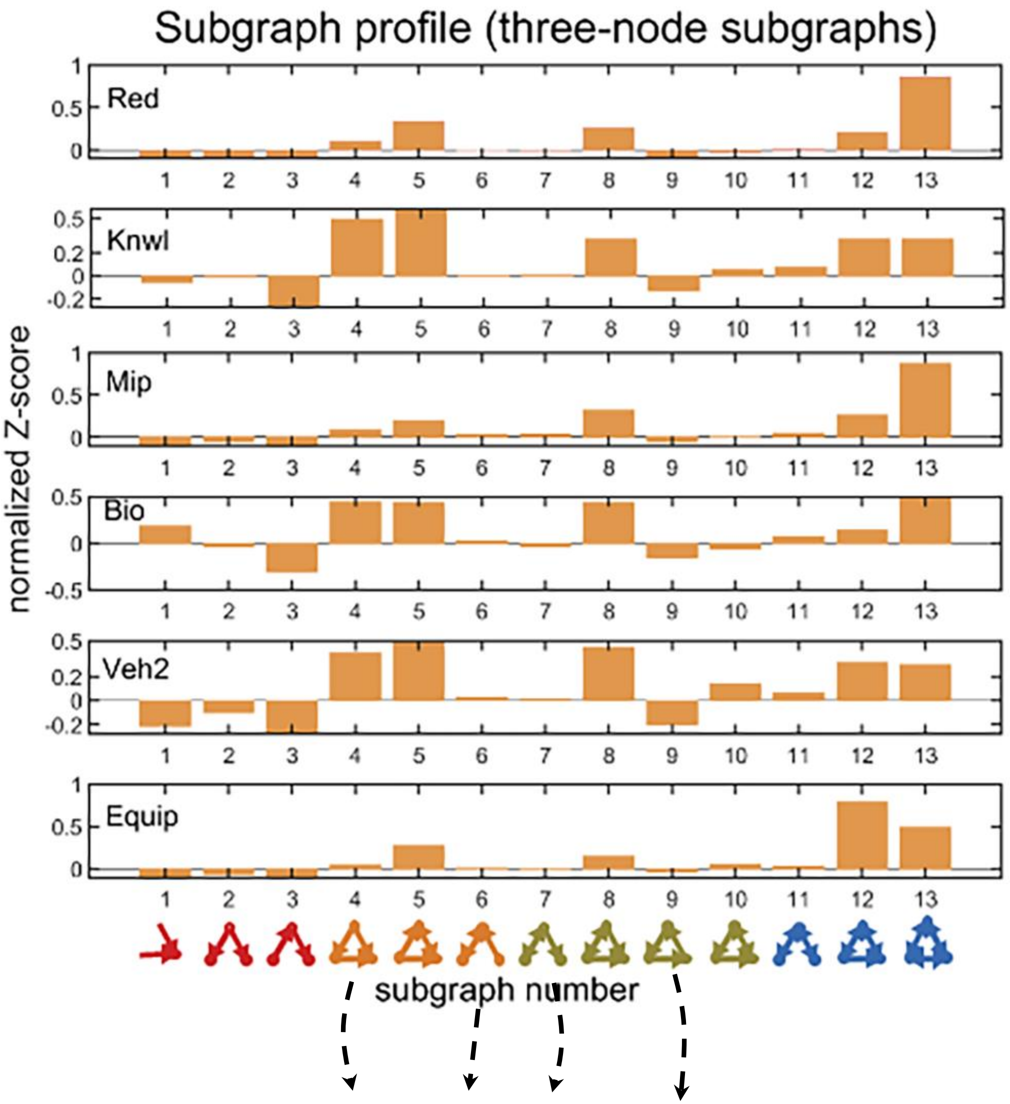
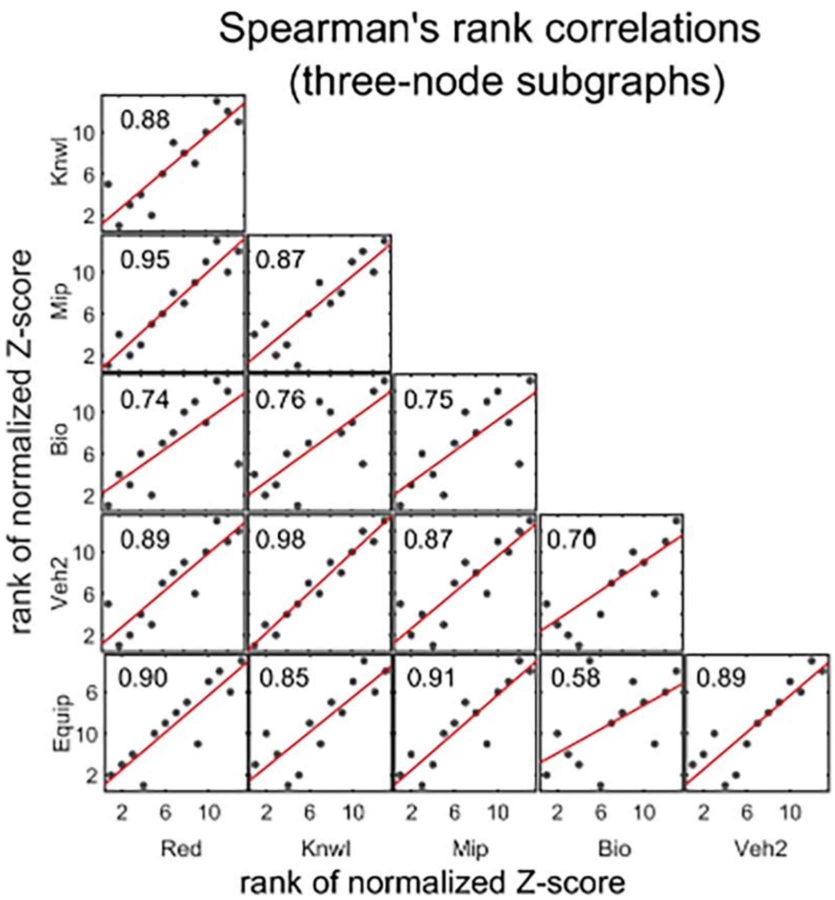
Subgraph Significance Profile (Z-Score)



$$\text{Z-Score} = \frac{\text{real freq} - \text{rand mean freq}}{\text{std rand}}$$

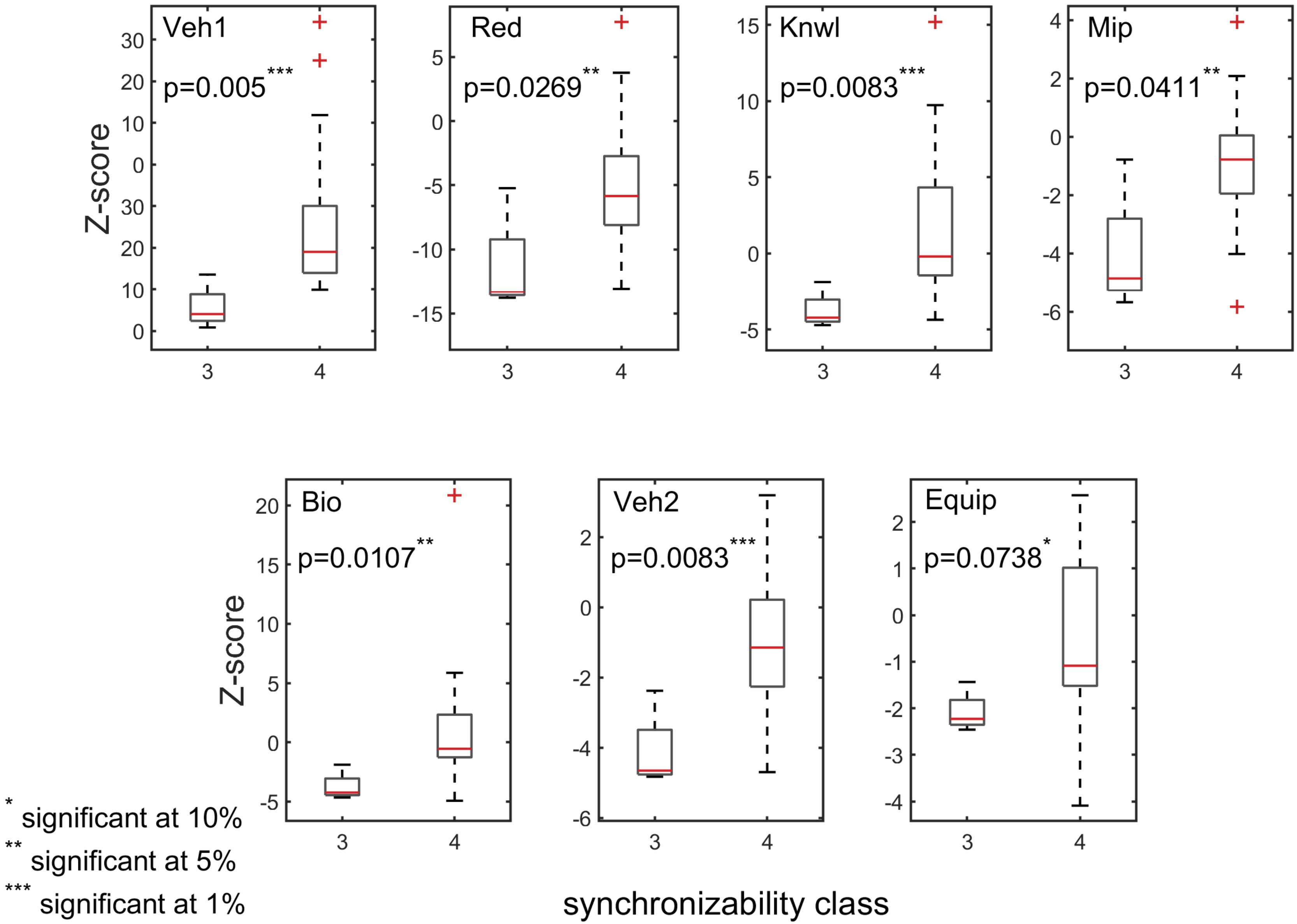




3-node, 3-edge subgraphs

https://www.nature.com/articles/s41598-020-75221-3

Z-Score Classified by Synchronizability Class (4-node, 4-edge Subgraphs)



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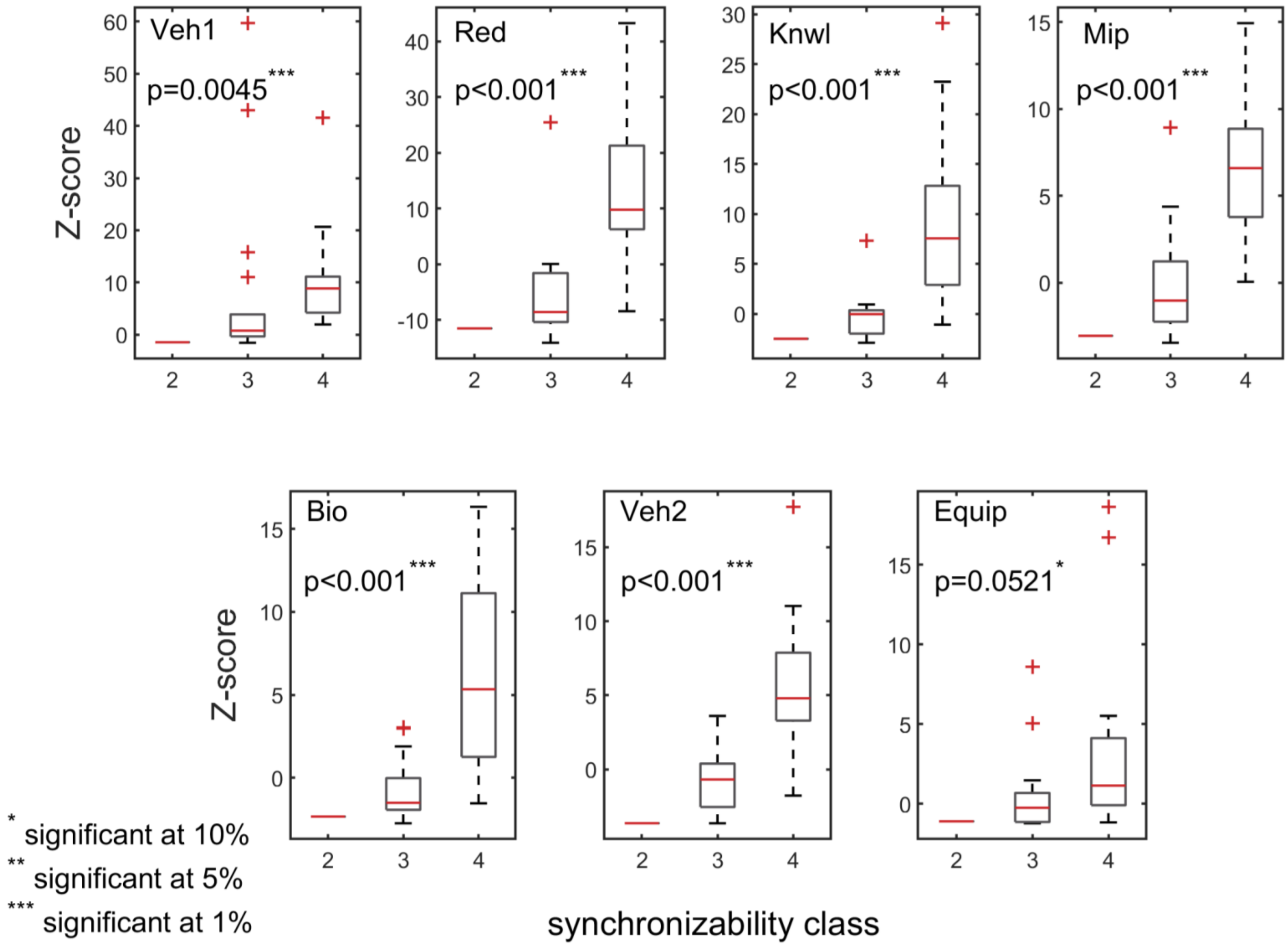
Z-Score Classified by Synchronizability Class (4-node, 5-edge Subgraphs)



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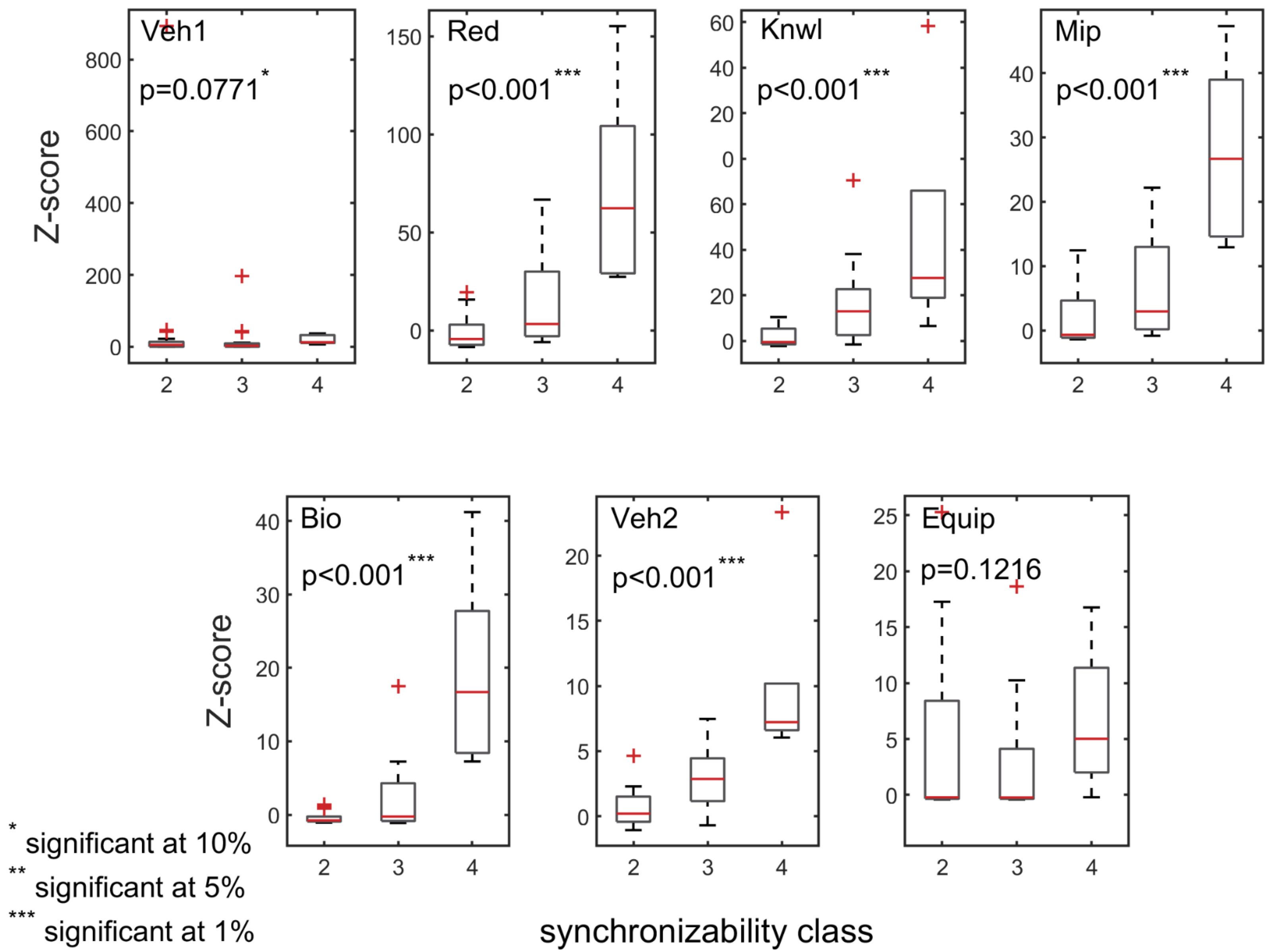
Z-Score Classified by Synchronizability Class (4-node, 6-edge Subgraphs)



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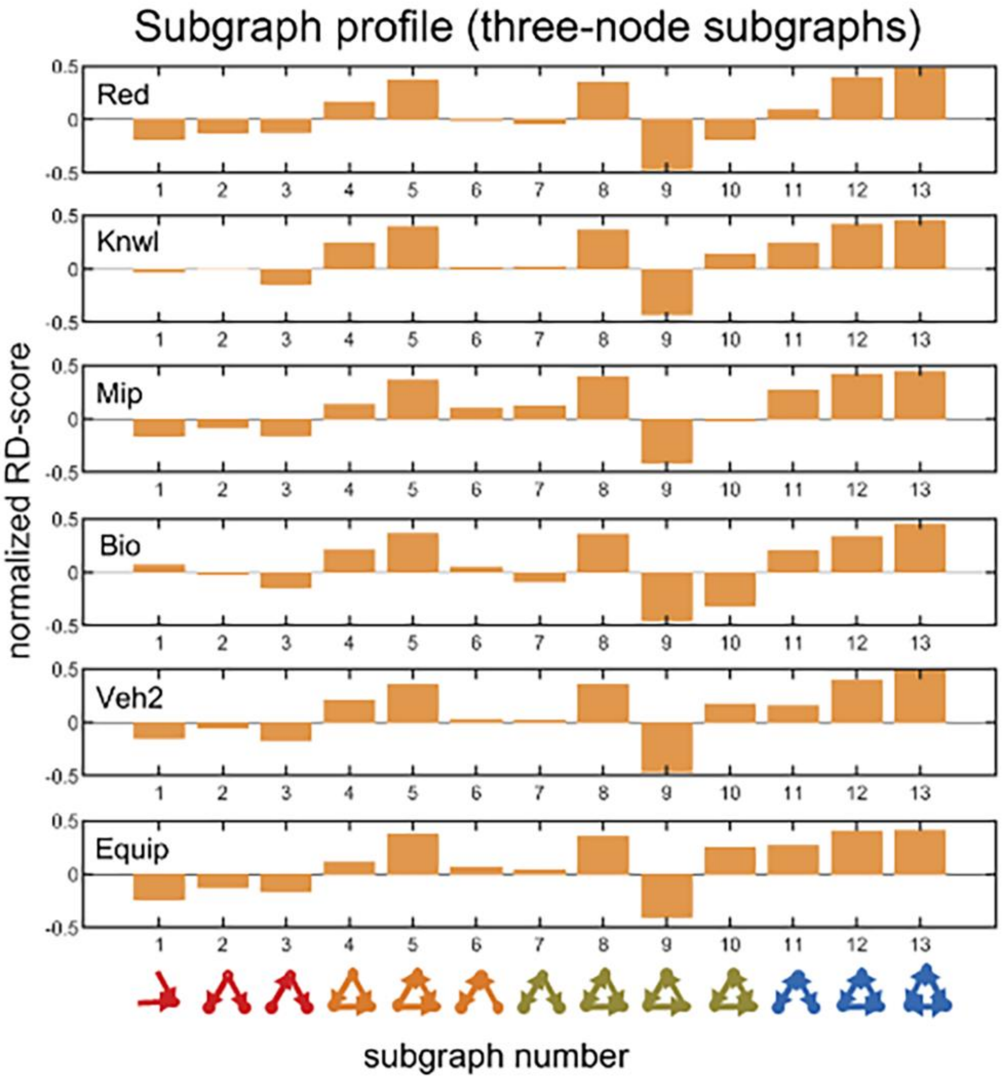
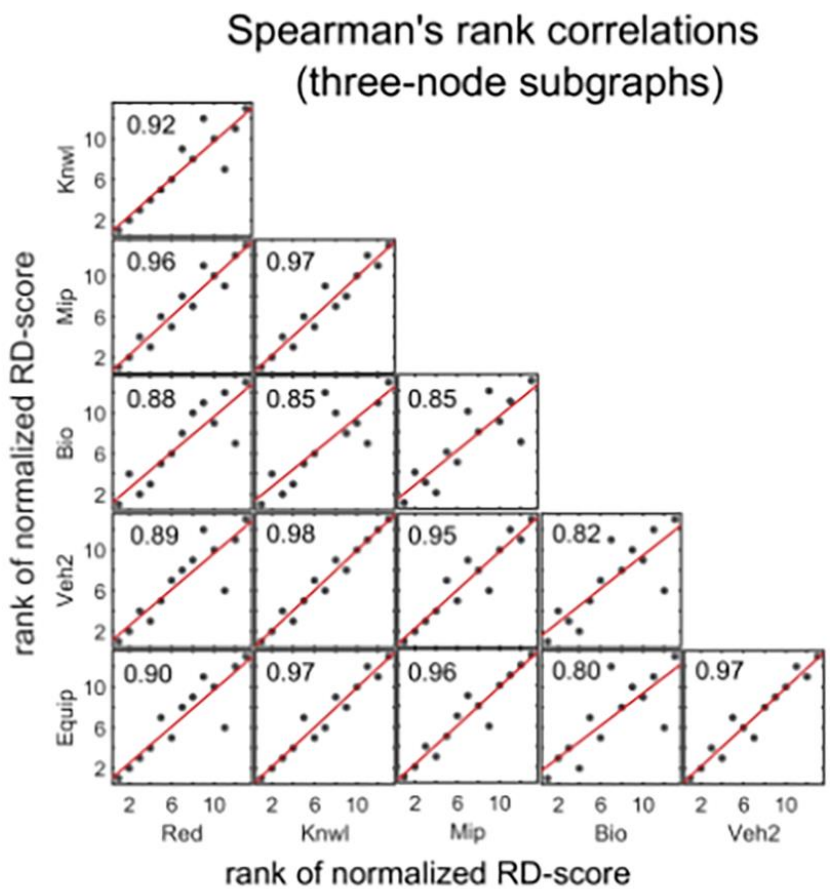
Subgraph Relative Difference Profile (RD-Score)

$$\text{RD-Score} = \frac{\text{real freq} - \text{rand mean freq}}{\text{real freq} + \text{rand mean freq}}$$





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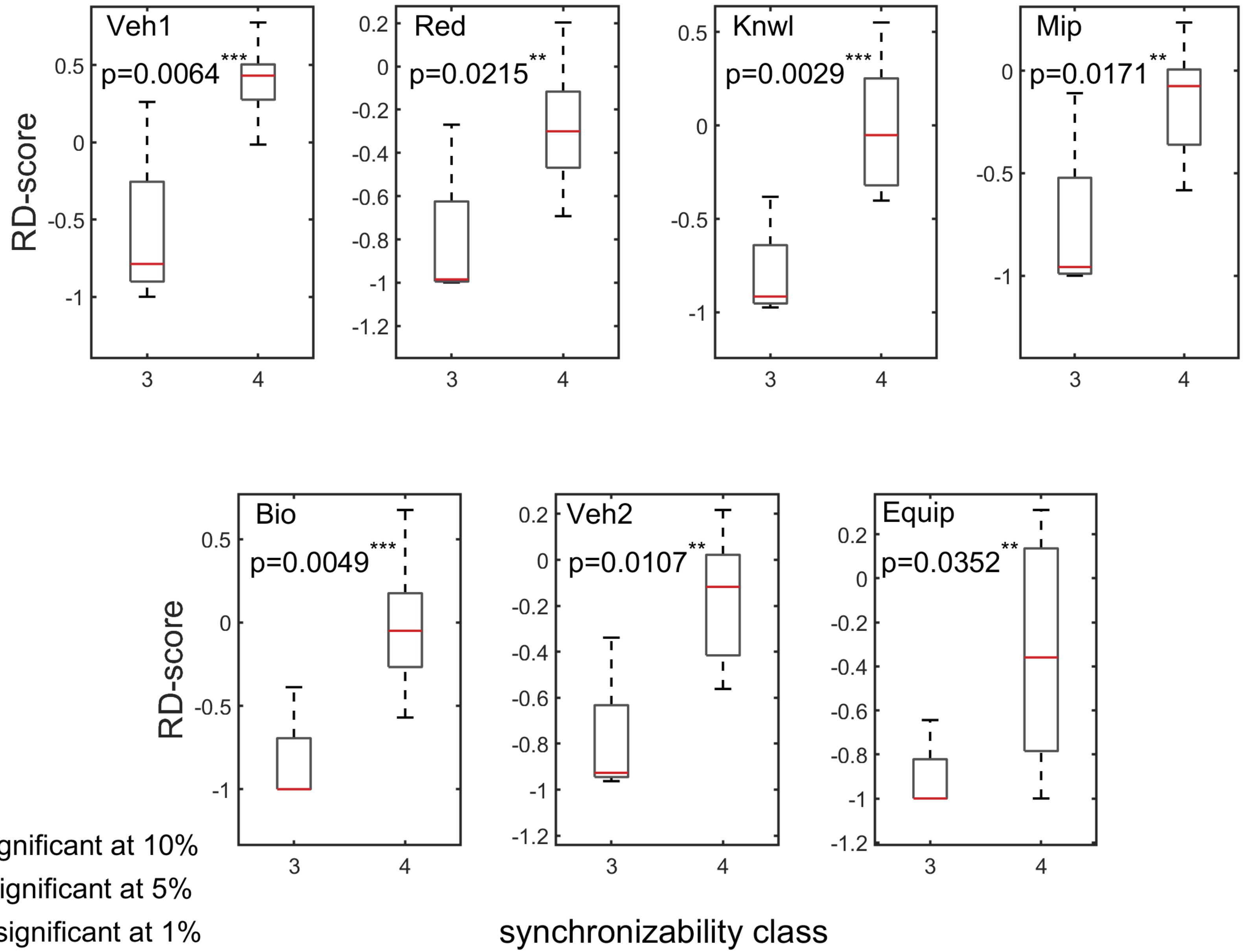
RD-Score Classified by Synchronizability Class (4-node, 4-edge Subgraphs)



* significant at 10%
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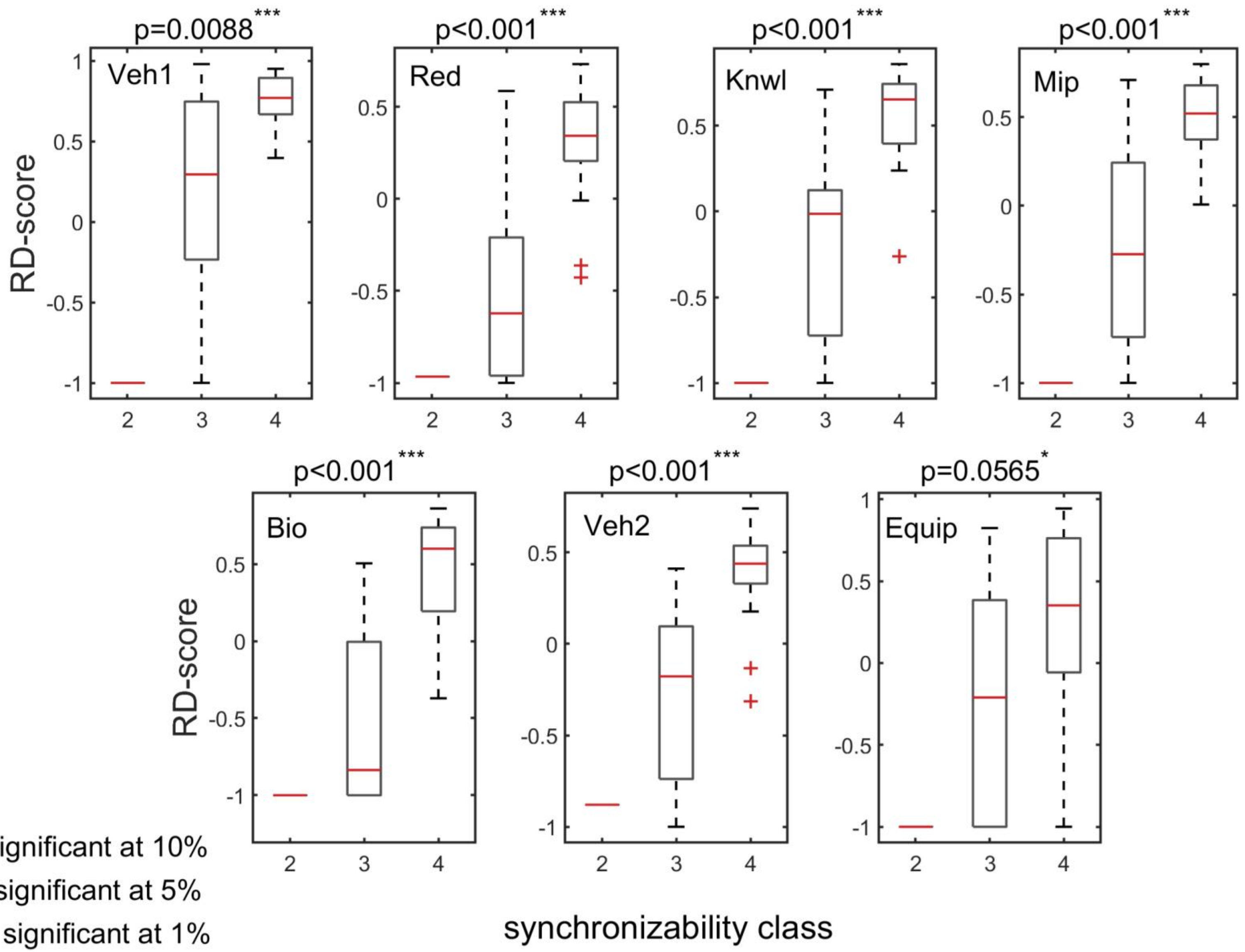
RD-Score Classified by Synchronizability Class (4-node, 5-edge Subgraphs)



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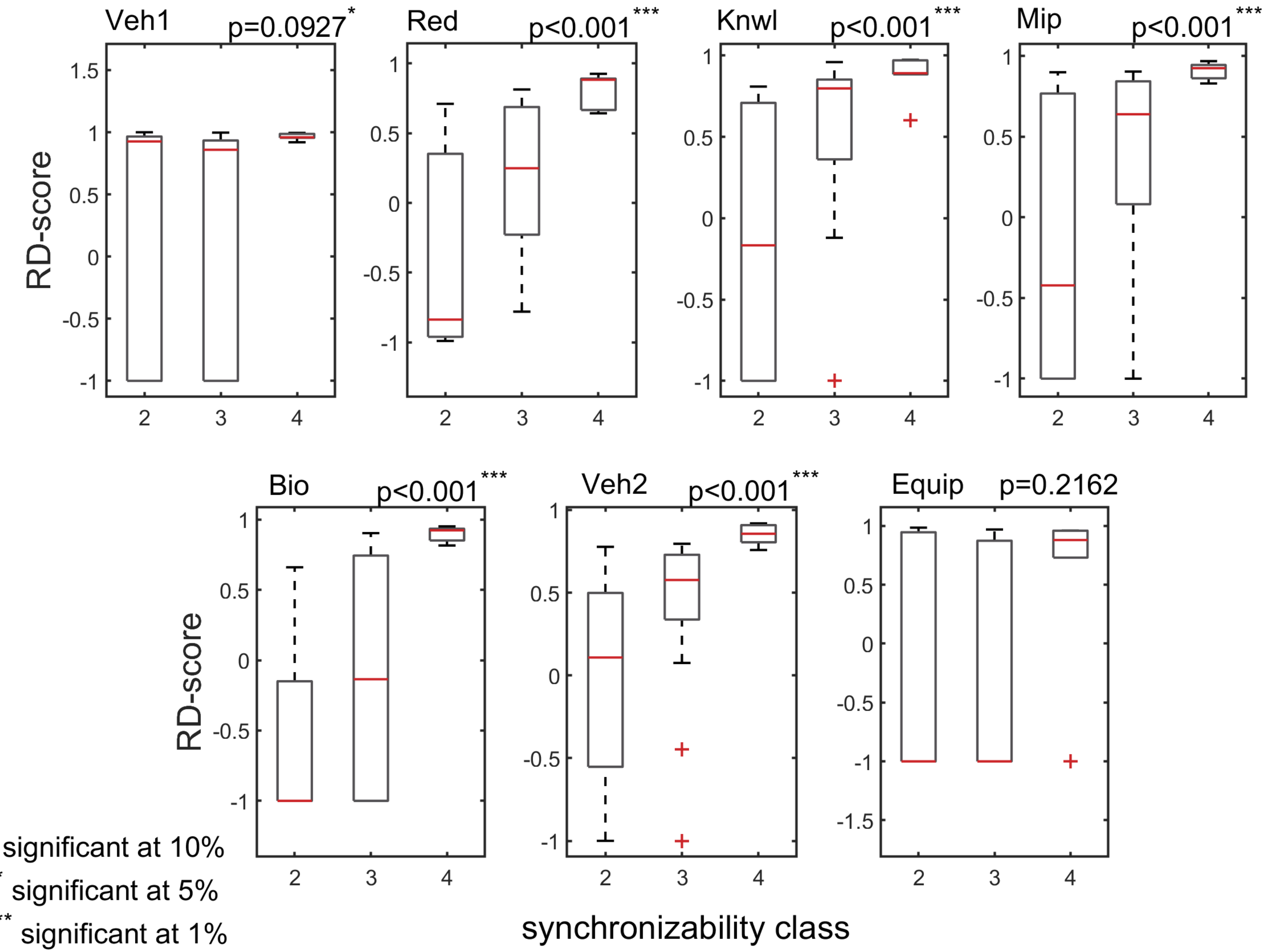
RD-Score Classified by Synchronizability Class (4-node, 6-edge Subgraphs)



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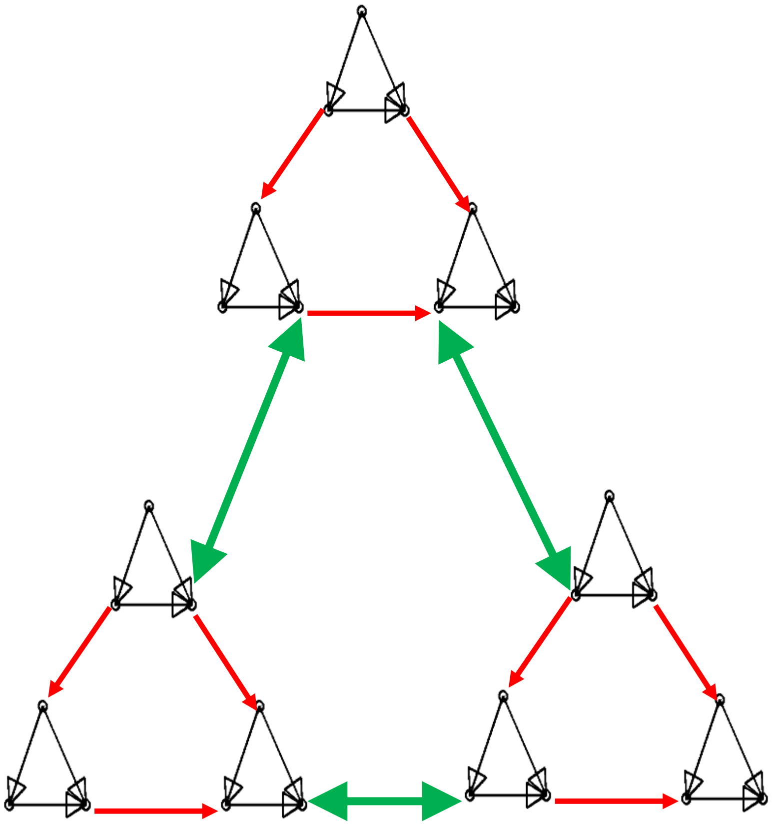
Summary

Large-scale design networks share repeated patterns of interdependent activities (routines) that are universal across many distinct organizations

The abundance of these design routines is highly correlated with their ability to synchronize and coordinate the design activity

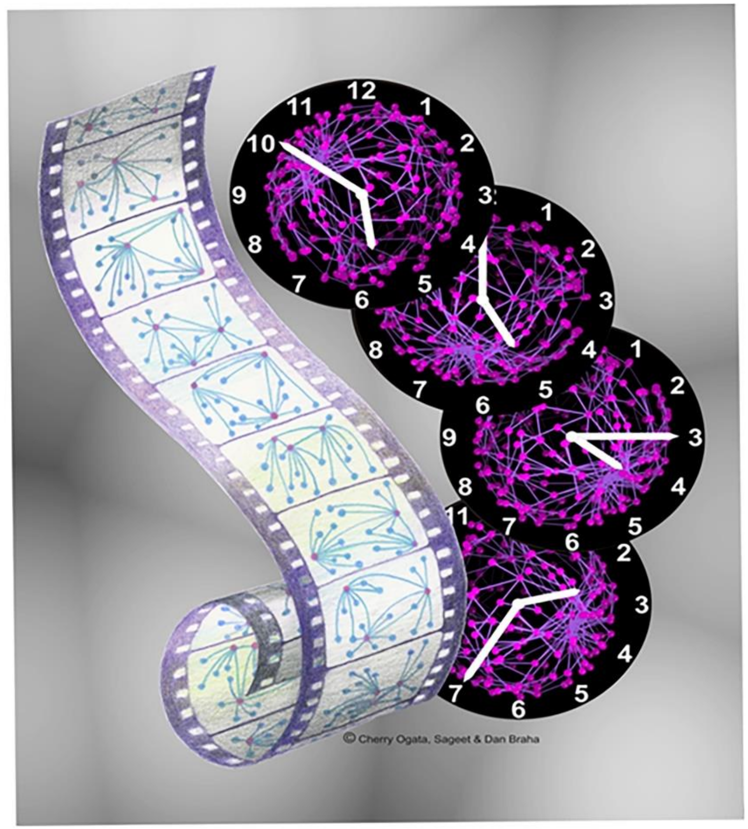
What is the Origin of the "Magical" Patterns?

Global and properties of local subgraphs contribute to the abundance of subgraphs



"subgraphs within subgraphs"

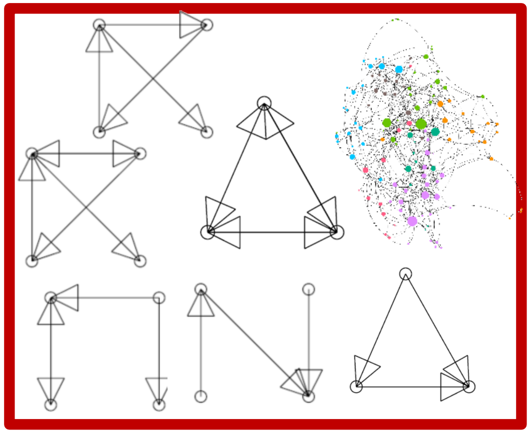
Braha D & Bar-Yam Y (2006)



Temporal nature of design networks and separation of time scales

Deeper Connection between engineering design and biology?

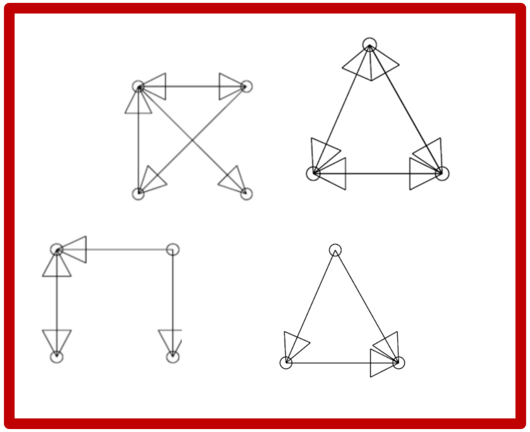
Variation



Diverse abundance of subgraphs in design networks. Some provide an advantage.

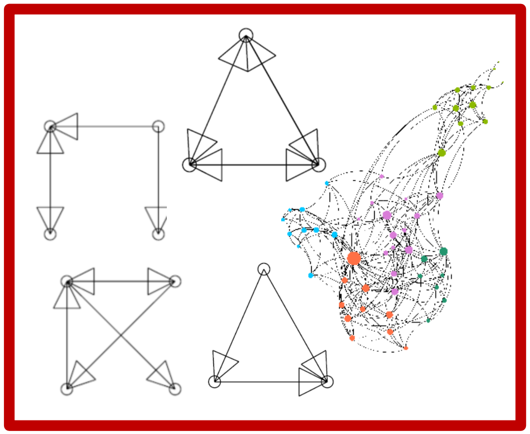
Selection and Transmission

(mimicry, copying, learning, re-use, best practices)



Selective pressures that favor more synchronizable subgraphs

New Design Networks



Increased abundance of subgraphs that enable better coordination and control

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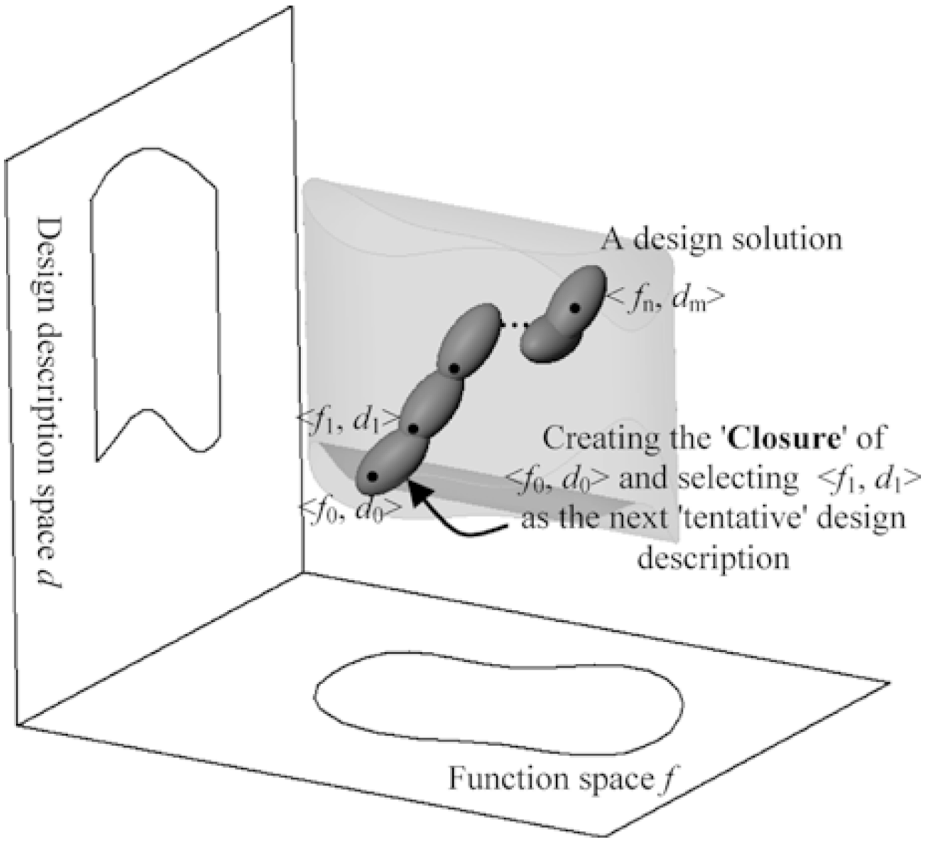
FIRE EXIT

‘Coupled Design Process’ Theory (RED 2003)



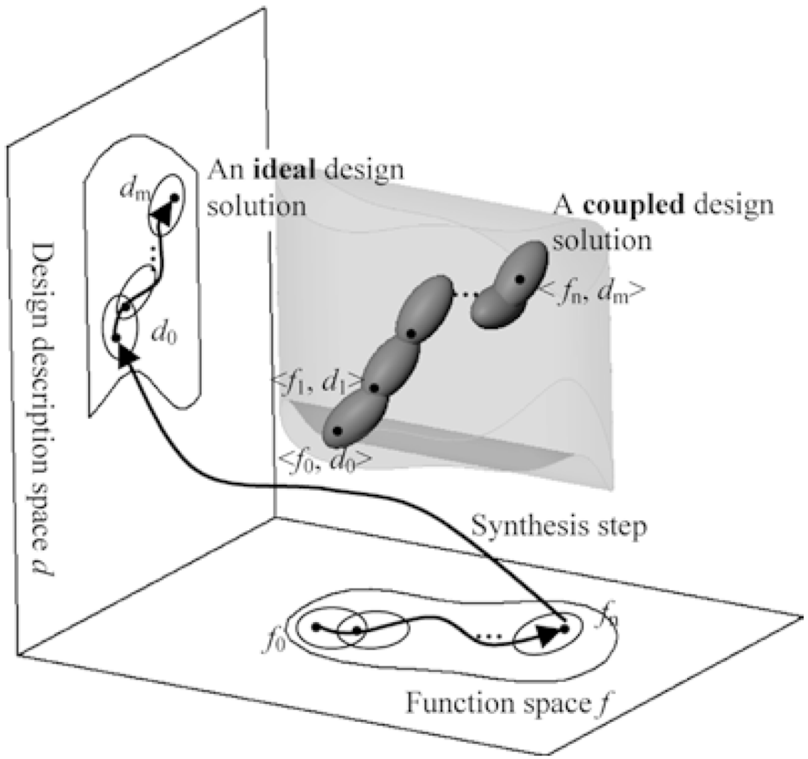
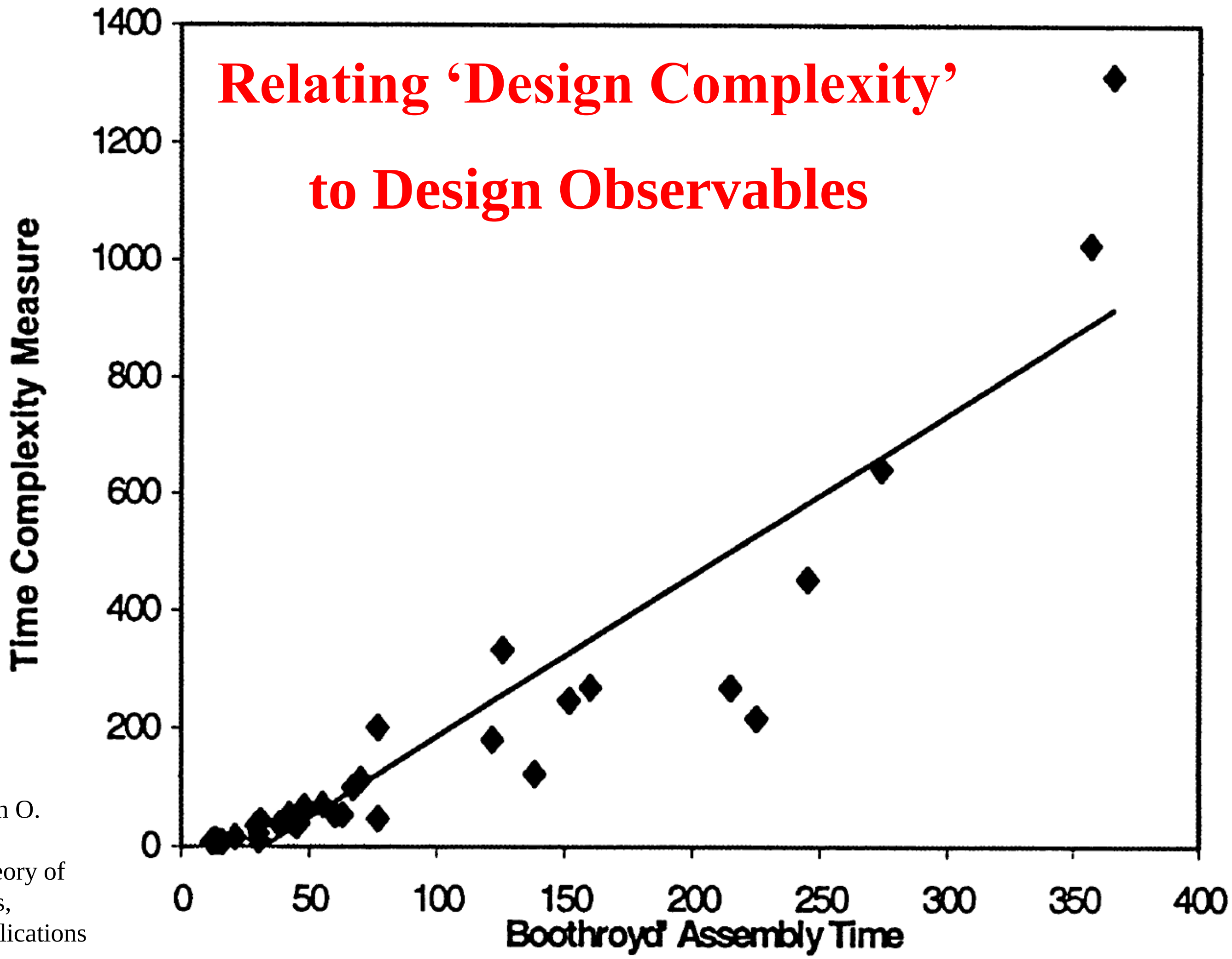


Fig. 5.

Relating 'Design Complexity' to Design Observables



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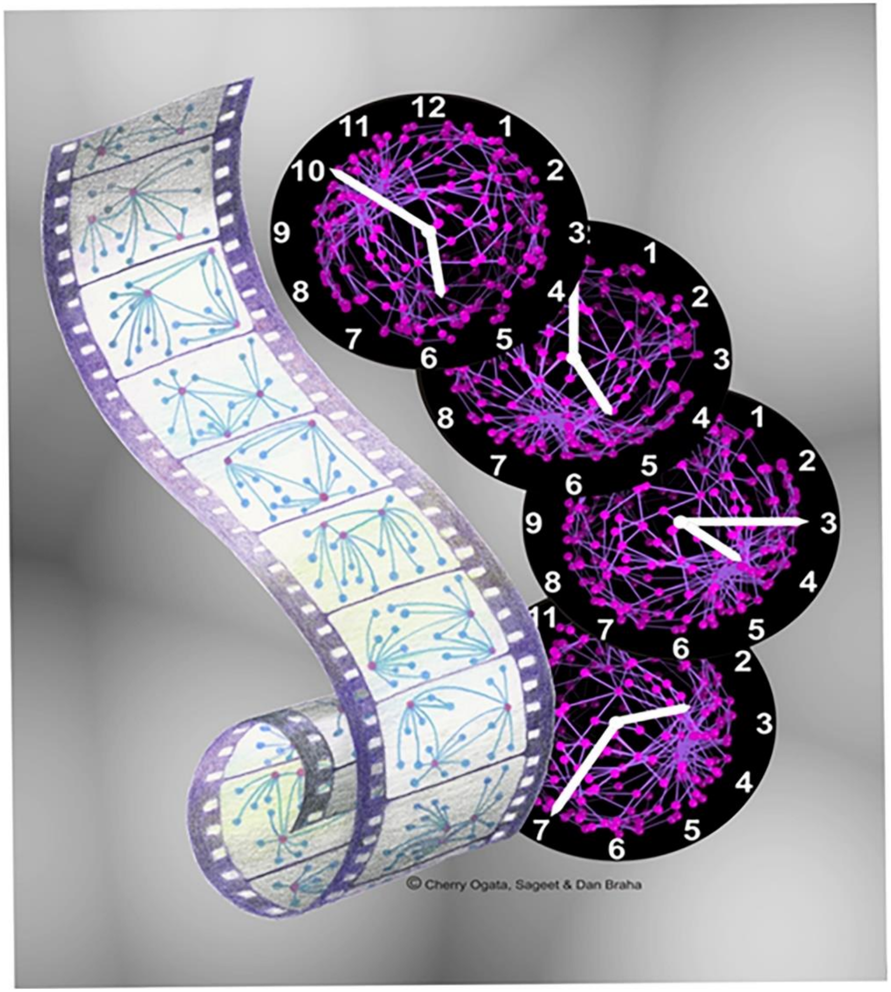
Temporal Complex Networks



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