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Architecting Resilient Systems with Design Structure Matrices and Network Topology Analysis

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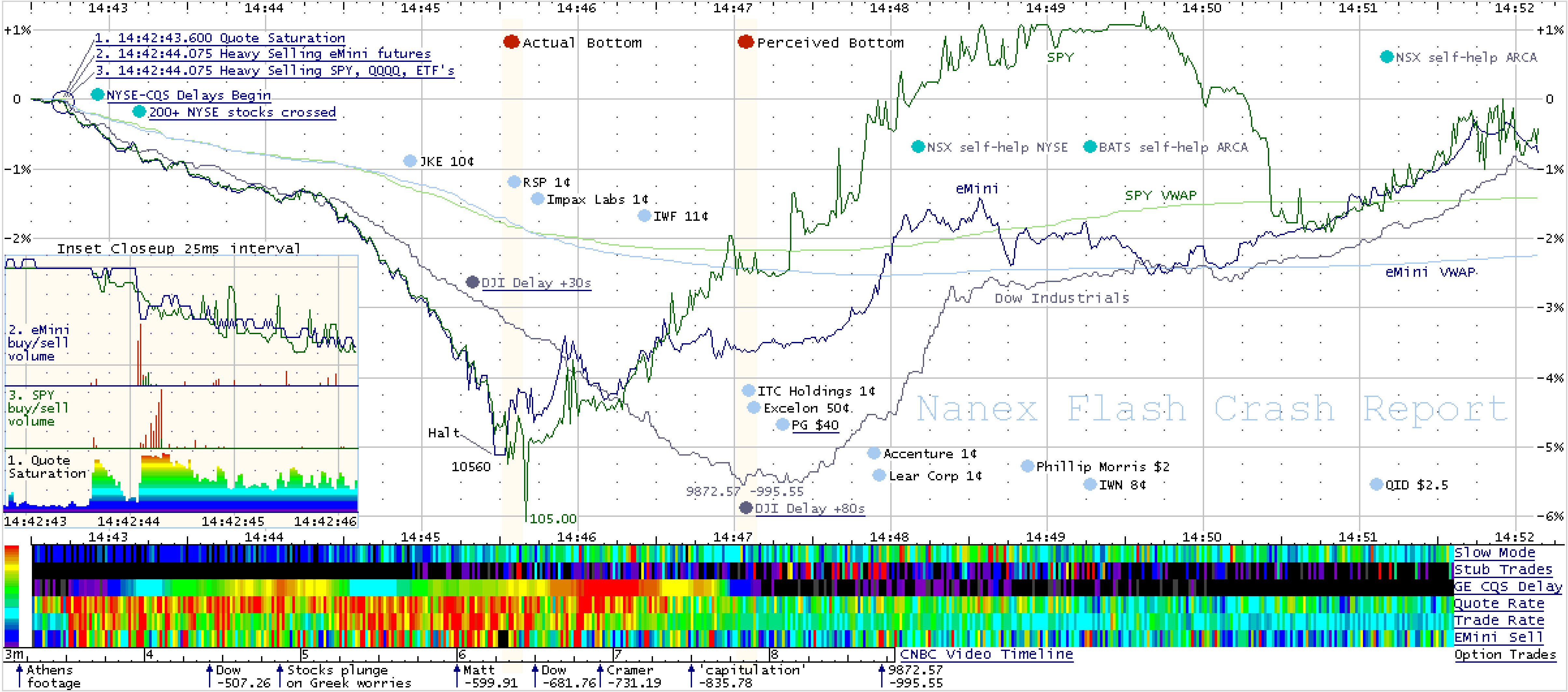
Why resilience?



Source: http://www.nanex.net/FlashCrashFinal/FlashCrashSummary.html

Agenda

Resilience as (non-functional) system life cycle property

Agenda

Resilience as (non-functional) system life cycle property

Life cycle properties as functions of architecture

Agenda

Resilience as (non-functional) system life cycle property

Life cycle properties as functions of architecture

Architectures as networks

Agenda

- Resilience as (non-functional) system life cycle property
- Life cycle properties as functions of architecture
- Architectures as networks
- Network properties as functions of network topology

Agenda

Resilience as (non-functional) system life cycle property

Life cycle properties as functions of architecture

Architectures as networks

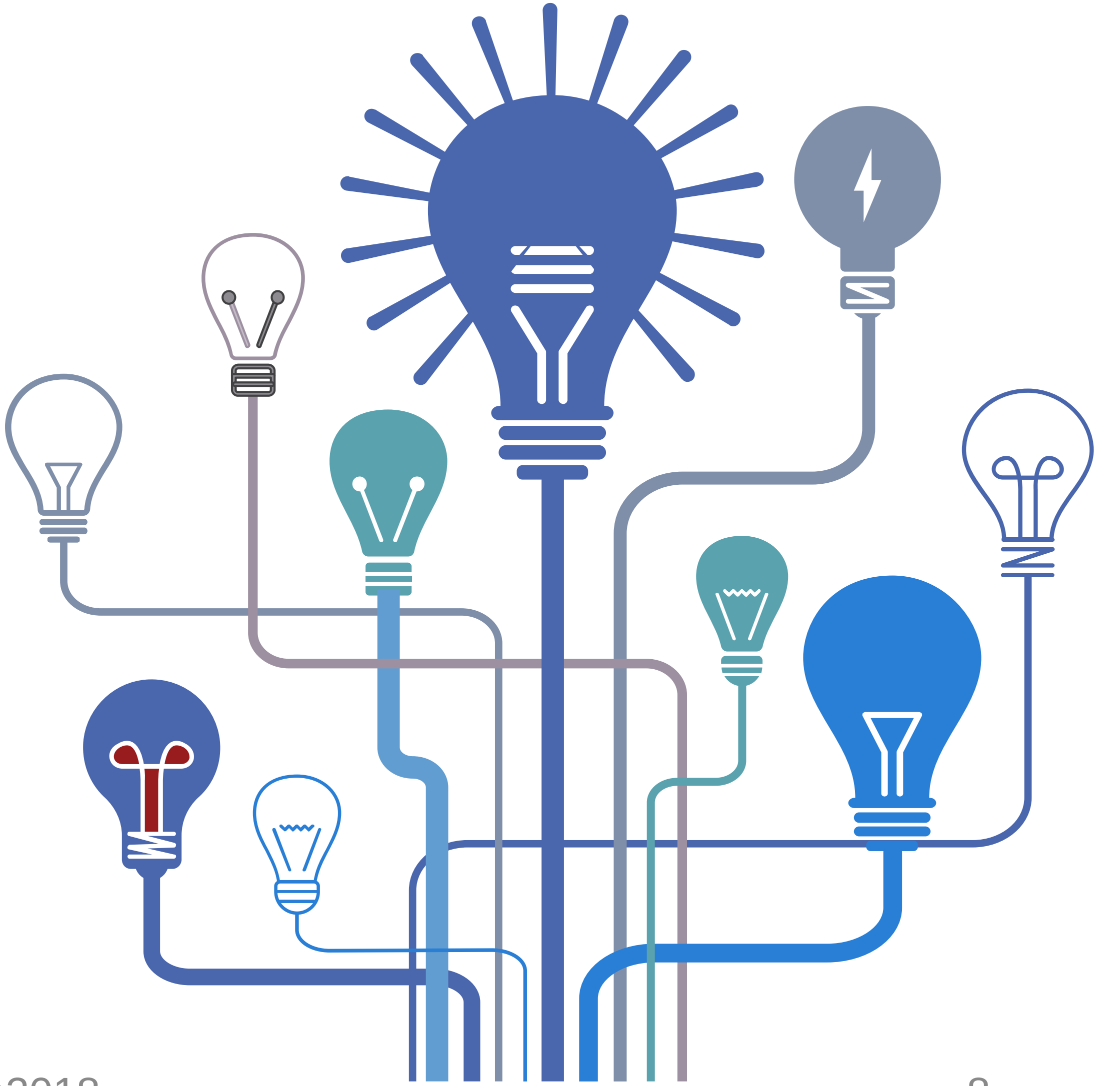
Network properties as functions of network topology

Resilience as function of network topology

Life cycle properties as functions of architecture

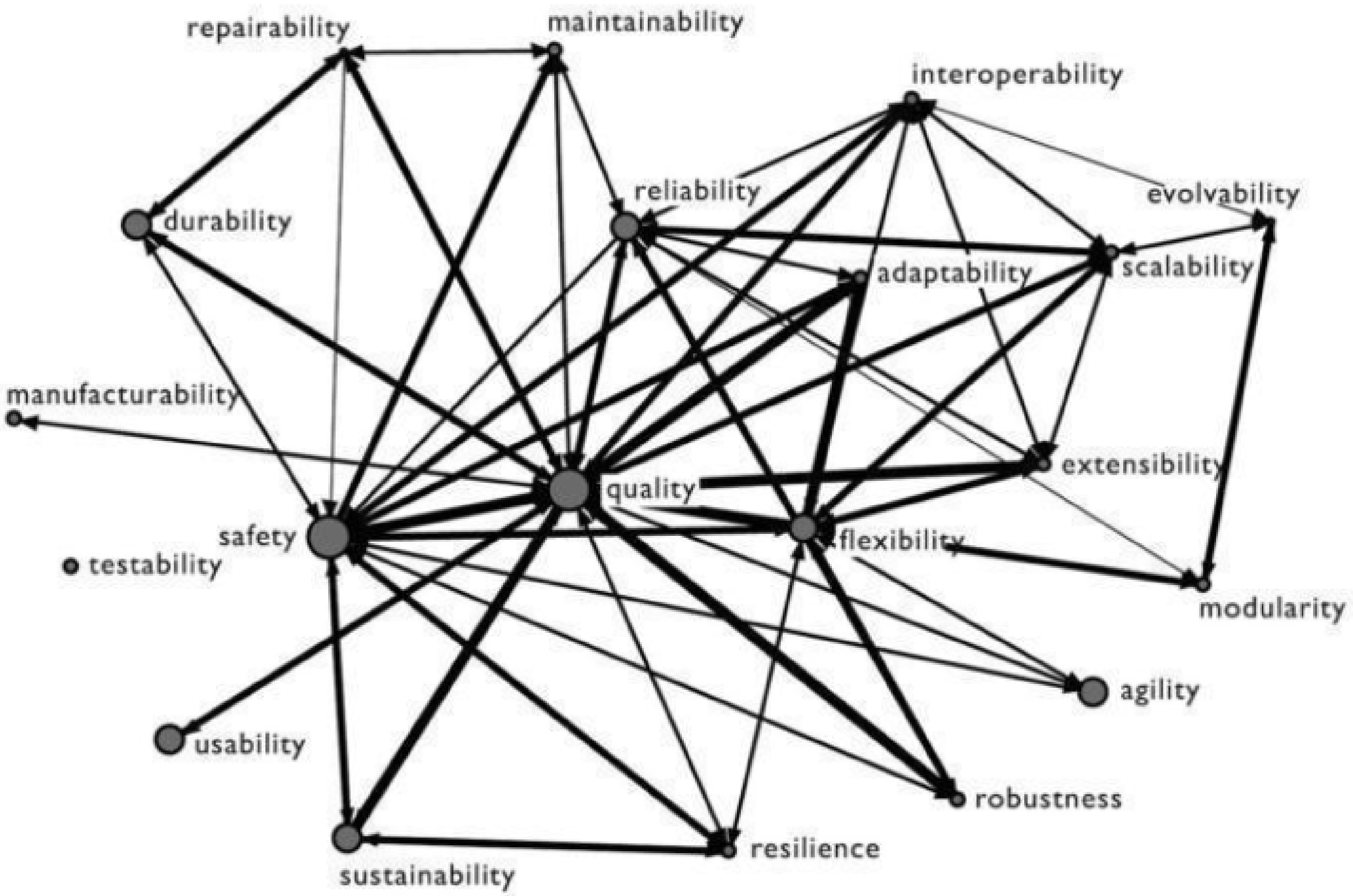
"We now understand better that the life cycle properties of systems (e.g. the ability of a system to be resilient to random or targeted attacks, or its ability to evolve) are largely determined by their underlying architecture."

-Olivier de Weck
Editor-in-chief of *Systems Engineering* (2013-18)
in May 2018 20th anniversary special issue



Source:
De Weck OL. Systems engineering 20th anniversary special issue. Systems Engineering. 2018;21:143–147. https://doi.org/10.1002/sys.21443

Resilience as system life cycle property



Source:
De Weck, Olivier L, et al. *Engineering Systems: Meeting Human Needs in a Complex Technological World*. MIT Press, 2016.

Resilience as system life cycle property

"Systems are no longer just conceived, designed, implemented, and operated in a linear fashion to satisfy stakeholder needs. They are ever-changing, coalescing into systems-of-systems driven by dynamic technological, economic and political forces, and they require us to constantly reassess, upgrade, and evolve them over time. That is why designing systems for specific desired life cycle properties such as *resilience*, *sustainability*, and *evolvability* is more important today than ever before."

-Olivier de Weck

Source:
De Weck OL. Systems engineering 20th anniversary special issue. Systems Engineering. 2018;21:143–147. https://doi.org/10.1002/sys.21443

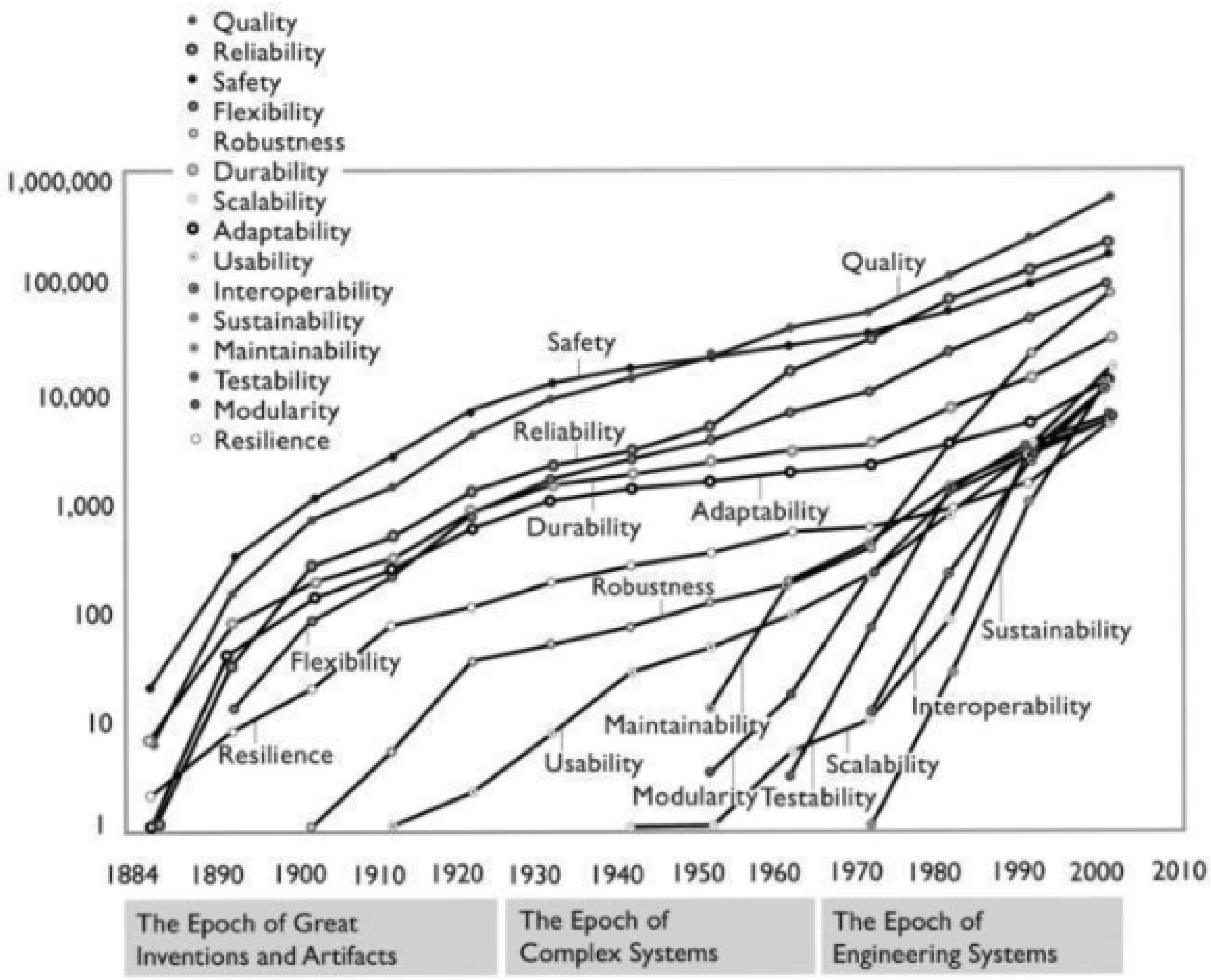
Life cycle properties as functions of architecture

"Today's systems exist in an extensive network of interdependencies as a result of opportunities afforded by new technology and by increasing pressures to become faster, better and cheaper for various stakeholders. But the effects of operating in interdependent networks has also created unanticipated side effects and sudden dramatic failures. These unintended consequences have led many different people from different areas of inquiry to note that some systems appear to be more resilient than others. This idea that systems have a property called 'resilience' has emerged and grown extremely popular in the last decade…"

-David D. Woods, co-author, *Resilience Engineering: concepts and precepts*

Source:
Woods, David D. "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering." *Reliability Engineering & System Safety*, vol. 141, 2015, pp. 5–9., doi:10.1016/j.ress.2015.03.018.

Resilience as system life cycle property



Source:
De Weck, Olivier L, et al. *Engineering Systems: Meeting Human Needs in a Complex Technological World*. MIT Press, 2016.

Life cycle properties as functions of architecture

01  Resilience as rebound

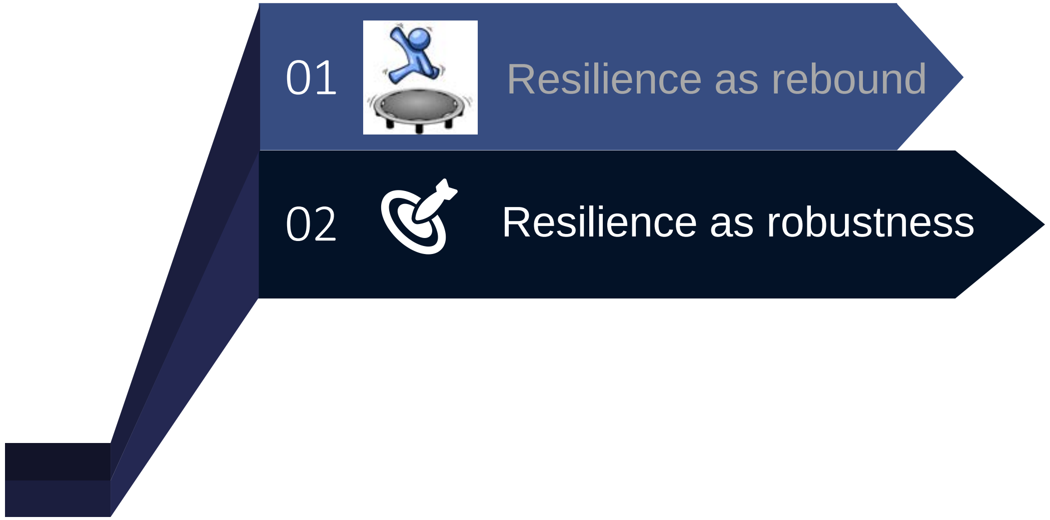
"This use of the label resilience as [1] – rebound – is common, but pursuing what produces better rebound merely serves to restate the question…."

"It is historically interesting that questions about resilience are often formulated around finding a way to explain variations in how systems rebound from challenge. But research progress has left this framing behind to focus on the fundamental properties of networks, systems and organizations that are able to build, modify and sustain the right kinds of adaptive capacities."

-David Woods 'Four Concepts for Resilience'

Source:
Woods, David D. "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering." *Reliability Engineering & System Safety*, vol. 141, 2015, pp. 5–9., doi:10.1016/j.ress.2015.03.018.

Life cycle properties as functions of architecture



"Resilience [2] – increased ability to absorb perturbations – confounds the labels robustness and resilience… this confound continues to add noise to work on resilience…"

"If an increase in robustness expands the set of disturbances the system can respond to effectively, the question remains what happens if the system is challenged by an event outside of the current set… The emerging understanding of heuristic and formal architectural principles points us to the fourth concept for resilience as some architectures are able to sustain the ability to adapt to future surprises over multiple cycles of change, or resilience [4]."

-David Woods 'Four Concepts for Resilience'

Source:
Woods, David D. "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering." *Reliability Engineering & System Safety*, vol. 141, 2015, pp. 5–9., doi:10.1016/j.ress.2015.03.018.

Life cycle properties as functions of architecture

"The third concept sees resilience as the opposite of brittleness, or, how to extend adaptive capacity in the face of surprise. Resilience [3] juxtaposes brittleness versus graceful extensibility…"

"Studies of how systems extend adaptive capacity to handle surprise have led to characterization of basic patterns in how adaptive systems succeed and fail. The starting point is exhausting the capacity to deploy and mobilize responses as disturbances grow and cascade-this pattern is called decompensation… where an increasing delay in recovery following disruption or stressor is an indicator of an impending collapse or a tipping point."

-David Woods 'Four Concepts for Resilience'

Source:
Woods, David D. "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering." *Reliability Engineering & System Safety*, vol. 141, 2015, pp. 5–9., doi:10.1016/j.ress.2015.03.018.

Life cycle properties as functions of architecture

"Resilience [4] refers to the ability [to] manage / regulate adaptive capacities of systems that are layered networks, and are also a part of larger layered networks, so as to produce sustained adaptability over longer scales…"

"Resilience [4] asks three questions: (1) what governance or architectural characteristics explain the difference between networks that produce sustained adaptability and those that fail to sustain adaptability? (2) What design principles and techniques would allow one to engineer a network that can produce sustained adaptability? (3) How would one know if one succeeded in their engineering?"

-David Woods 'Four Concepts for Resilience'

Source:
Woods, David D. "Four Concepts for Resilience and the Implications for the Future of Resilience Engineering." *Reliability Engineering & System Safety*, vol. 141, 2015, pp. 5–9., doi:10.1016/j.ress.2015.03.018.

Architectures as networks

“Technical systems have network structures.
Social, organizational, and technical elements of most sociotechnical systems are interconnected through exchanges of resources (information, energy, and material) and dependencies among various decision parameters in various stages of systems life cycles. Such dependencies are often not uniform and follow structured patterns that can naturally be modeled using complex networks.”

Heydari & Pennock,
in May 2018 20th anniversary special issue of
Systems Engineering

Source
Heydari, Babak, and Michael J. Pennock. “Guiding the Behavior of Sociotechnical Systems: The Role of Agent-Based Modeling.” Systems Engineering, vol. 21, no. 3, 2018, pp. 210–226., doi:10.1002/sys.21435.

Architectures as networks

"Has systems engineering become less waterfall-driven, process-oriented, and heavyweight, and more agile and model-based…?"

"The trends for technology terms [such as] "network AND systems engineering" [and] "graph AND systems engineering"… all suggest this is true."

- Sarah Sheard, INCOSE Fellow,
in May 2018 20th anniversary special issue of
Systems Engineering

	network (K)	graph AND systems engineering
1998	12.663	1.2
1999	12.493	3.352
2000	12.643	1.72
2001	12.457	2.21
2002	13.252	3.926
2003	13.710	1.79
2004	14.116	2.861
2005	14.693	2.972
2006	14.724	3.068
2007	15.087	2.09
2008	15.562	5.144
2009	16.129	4.898
2010	15.835	4.097
2011	15.740	4.711
2012	15.383	4.593
2013	15.376	5.091
2014	15.335	5.246
2015	15.804	8.657
2016	16.400	8.700
2017	17.025	7.037

Source
Sheard, Sarah A. "Evolution of Systems Engineering Scholarship from 2000 to 2015, with Particular Emphasis on Software." *Systems Engineering*, vol. 21, no. 3, 2018, pp. 152–171., doi:10.1002/sys.21441.

Architectures as networks

“The overall difficulty with applying simple network models to engineering systems is that often nodes and links or node relationships are not uniform and not transitive. In an acquaintance network, for example, the relation of *knowing someone* is reversible, thus the network is undirected…

This is not the case for most engineering systems, where at any level of abstraction components are assembled or arranged in particular ways to work properly. Moreover, the nodes and links rarely can be put in the same category. These are *hybrid* networks: in other words, networks comprised of nodes (and maybe links) of different types...”

- Bounova & de Weck

Source:
Bounova, Gergana, and Olivier L De Weck. “Augmented Network Model for Engineering System Design.” Unifying Themes in Complex Systems, 2010, pp. 323–330., doi:10.1007/978-3-540-85081-6_41..

Architectures as networks

"This does not mean that simple metrics from a pure graph model could not be useful for engineering analysis. The key in this type of modeling is

i) picking the right level of abstraction,

ii) encoding the right level of detail."

- Bounova & de Weck

Source:
Bounova, Gergana, and Olivier L De Weck. "Augmented Network Model for Engineering System Design." Unifying Themes in Complex Systems, 2010, pp. 323–330., doi:10.1007/978-3-540-85081-6_41..

Architectures as networks

"A growing literature on 'network motifs' seeks to identify and abstract functional units within networks representing a system's form. These tools may be used in concert with existing approaches emphasizing decomposition and modularity."

-David Broniatowski
in May 2018 20th anniversary special issue of
Systems Engineering

Source:
Broniatowski, David A. "Building the Tower without Climbing It: Progress in Engineering Systems." Systems Engineering, vol. 21, no. 3, 2018, pp. 259–281., doi:10.1002/sys.21426.

Architectures as networks

"Our findings suggest that the measures of system lifecycle properties may depend on the adopted network representation of the system. In other words, the particular abstraction used to model a given system as a network has an impact on how the structure of this specific representation relates to properties of the system…Thus, future work should examine how the choice of network representation interacts with measures of system lifecycle properties.

-Feitosa & Broniatowski

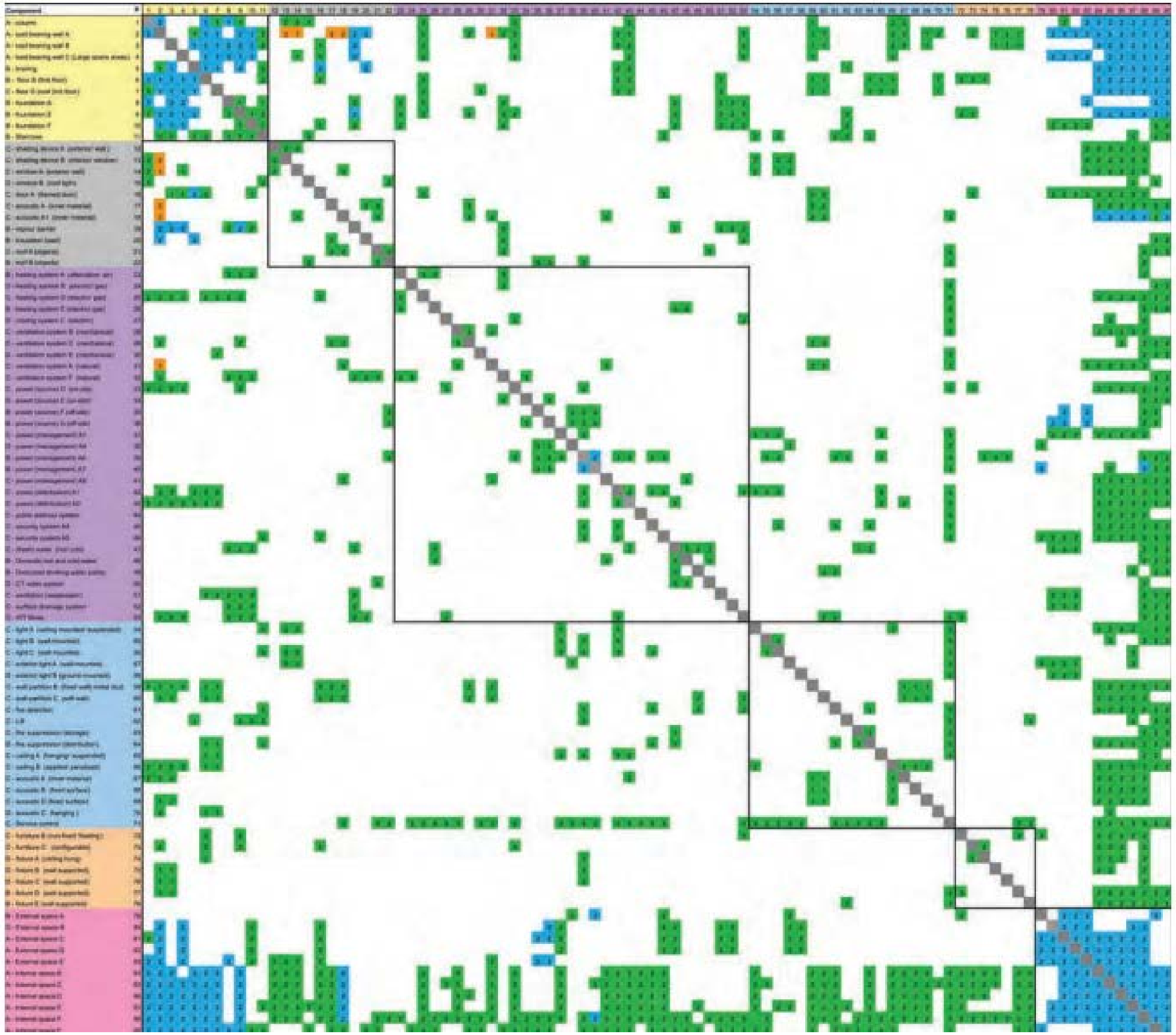
Source:
Feitosa, Douglas, and David Broniatowski. "Not All Networks Are Equal: Empirical Analysis of Flexibility and Controllability in Software Systems." *Proceedings of the 2016 Industrial and Systems Engineering Research Conference*.

Architectures as networks: the Design Structure Matrix

"What Is the DSM?

The DSM is a network modeling tool used to represent the elements comprising a system and their interactions, thereby highlighting the system's architecture (or designed structure). DSM is particularly well suited to applications in the development of complex, engineered systems..."

-Eppinger & Browning



Source:
Eppinger, Steven D.; Browning, Tyson R. Design Structure Matrix Methods and Applications. The MIT Press.

Architectures as networks: the Design Structure Matrix

"*DSM* is an *n* x *n* matrix in which rows and columns represent the components and activities within a system. The cell (*i*, *j*) represents the information exchange and dependency patterns associated with the components *i* and *j*. The matrix enables quickly identifying which functions depend on results from which other functions."

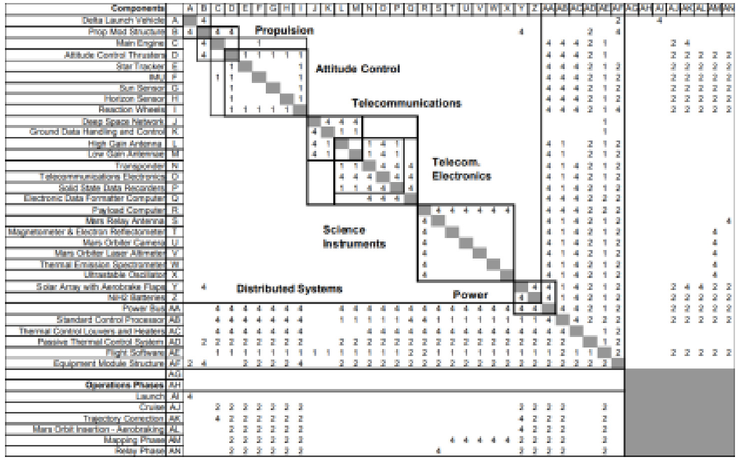
-Madni & Sievers (INCOSE Fellows)
in May 2018 20th anniversary special issue of
Systems Engineering

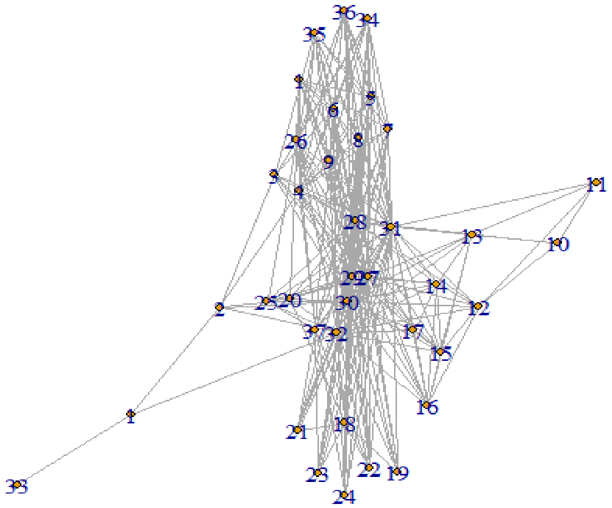
Source:
Madni, Azad M., and Michael Sievers. "Model-Based Systems Engineering: Motivation, Current Status, and Research Opportunities." *Systems Engineering*, vol. 21, no. 3, May 2018, pp. 172–190., doi:10.1002/sys.21438.

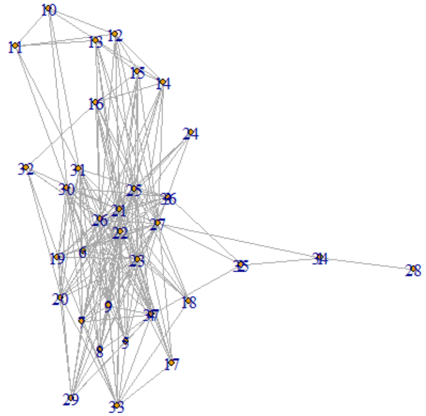
Architectures as networks: the Design Structure Matrix

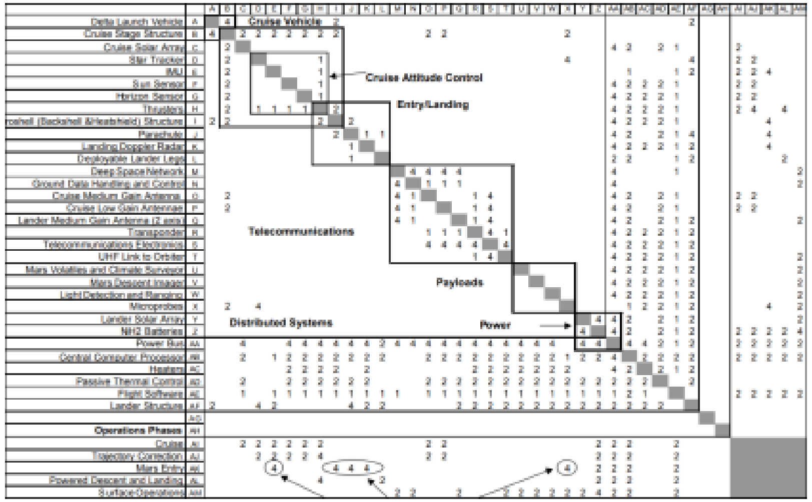
"Compared with other network modelling methods, the primary benefit of DSM is the graphical nature of the matrix display format. The matrix displays a highly compact, easily scalable, and intuitively readable representation of a system architecture..."

-Eppinger & Browning









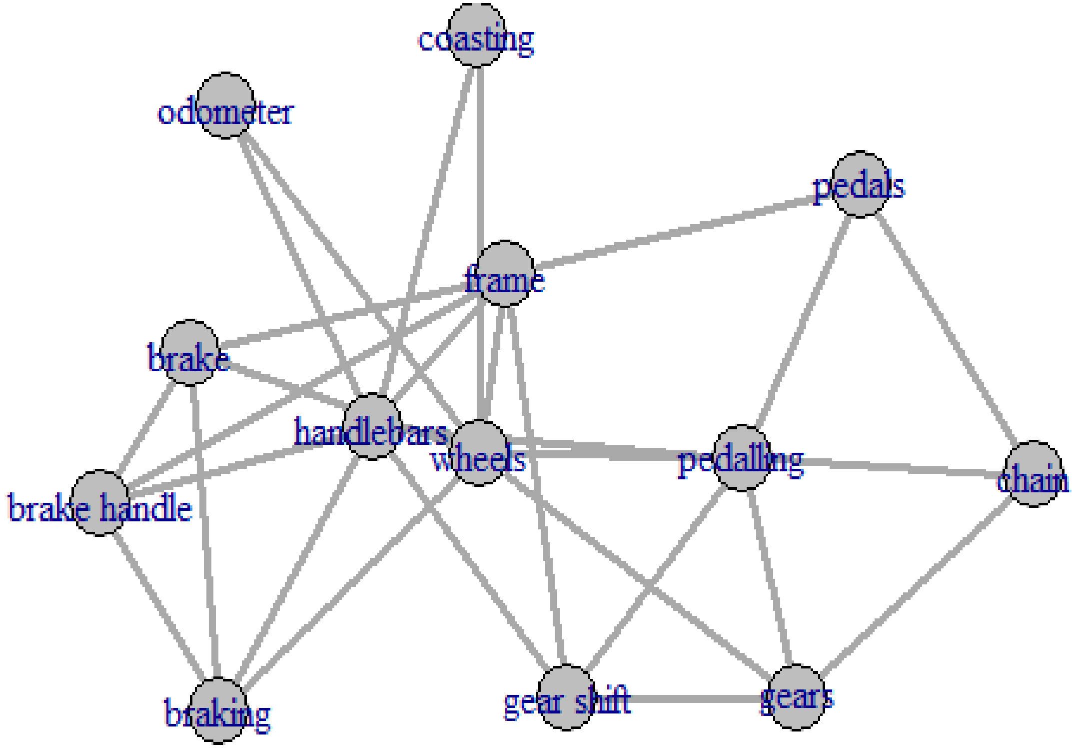
Source:
Eppinger, Steven D.; Browning, Tyson R.. Design Structure Matrix Methods and Applications. The MIT Press. DSM from Tim Brady, MIT Thesis, 'Utilization of Dependency Structure Matrix Analysis to Assess Implementation of NASA's Complex Technical Projects'.

Architectures as networks: the Design Structure Matrix

"The adjacency matrix [of a network] is simply the binary version of a DSM (placing ones in the cells with marks and zeros elsewhere)."

-Eppinger & Browning

	Components	Wheels	Gears	Chain	Pedals	Handlebars	Frame	Brake	Brake Handle	Gear Shift	Odometer	**Operational Phases**	Pedalling	Coasting	Braking
Components		A	B	C	D	E	F	G	H	I	J	K	L	M	N
Wheels	A		4				2	4			2		4	4	4
Gears	B	4		4						4			2		
Chain	C		4		4								4		
Pedals	D			4			2						4		
Handlebars	E						2		2	2	2		2	2	4
Frame	F	2			2	2		2	2	2					
Brake	G	4					2		4						4
Brake Handle	H					2	2	4							4
Gear Shift	I		4			2	2						2		
Odometer	J	2				2									
Operational Phases	K														
Pedalling	L	4	2	4	4	2				2					
Coasting	M	4				2									
Braking	N	4				4		4	4						



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Eppinger, Steven D.; Browning, Tyson R.. Design Structure Matrix Methods and Applications. The MIT Press. DSM from Tim Brady, MIT Thesis, 'Utilization of Dependency Structure Matrix Analysis to Assess Implementation of NASA's Complex Technical Projects'.

Architectures as networks

The above suggests that while not a universal modeling tool, networks are especially useful as design tools for building specific behaviors, such as resilience, into system architectures, an understudied area of application. The Design Structure Matrix is an especially useful tool in this domain.

Conclusions

Technical systems have network structure

Network structure useful for design purposes

Networks not good models of generic system behavior

But network statistics useful for modeling specific behaviors

Networks useful for designing specific behaviors into architecture

Especially behaviors centered on communication/ exchange of information

Methodology, Findings and Conclusions

Resilience as function of network topology

Resilience as function of network topology: how to model?

"The name **Resilience Engineering** was coined in the book Resilience Engineering: Concepts and Precepts (Hollnagel et al 2006). The authors make clear in this book that Resilience Engineering has to do with the resilience of the organisations that design and operate engineered systems and not with the systems themselves… To fully achieve [the resilience of engineered systems] SE also needs to consider the resilience of those organisational and human systems which enable the life cycle of an engineered system. The techniques or design principles used to assess and improve the resilience of engineered systems across their **life cycle** are elaborated by Jackson and Ferris."

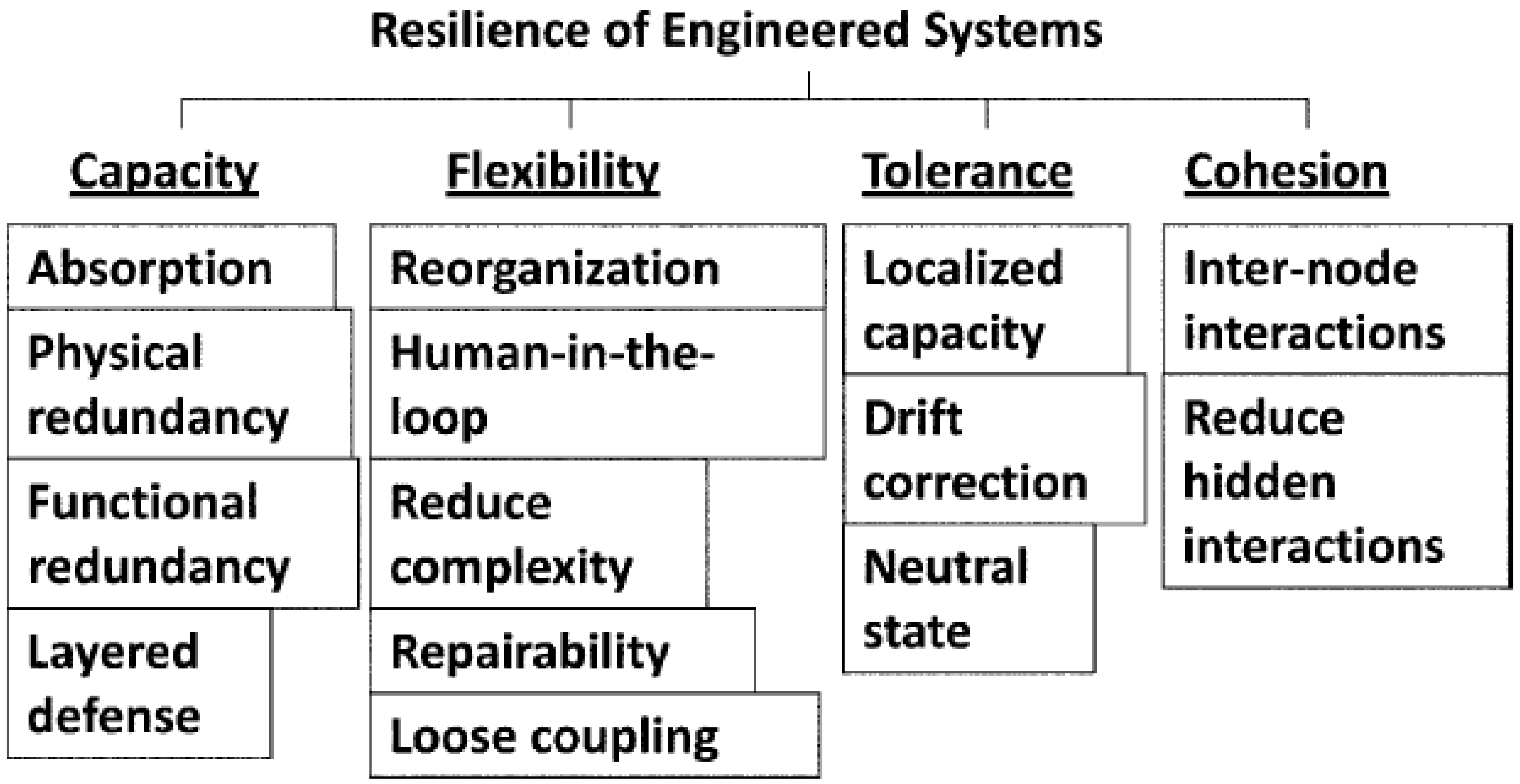
-SEBoK 'System Resilience'

Source:
SEBoK contributors, "System Resilience," *SEBoK,* , https://www.sebokwiki.org/w/index.php?title=System_Resilience&oldid=53151 (accessed August 20, 2018).

Resilience as function of network topology: how to model?

1

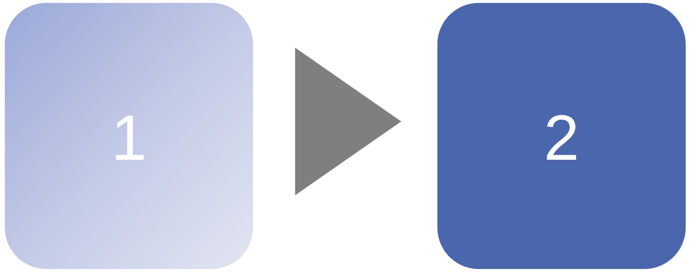
Identify networked architectural property as proxy for resilience



-Scott Jackson, INCOSE Fellow, and T.L.J. Ferris

Source:
Jackson, Scott, and Timothy L. J. Ferris. “Resilience Principles for Engineered Systems.” *Systems Engineering*, vol. 16, no. 2, 2012, pp. 152–164., doi:10.1002/sys.21228.

Resilience as function of network topology: how to model?



Identify networked architectural property as proxy for resilience

Identify leverage points to achieve architectural property

"The principles of leverage at the interfaces, policy triage, stable intermediate forms, and ensuring collaboration combine to a focus on communications as architecture…

From leverage at the interfaces we conclude that interfaces are the architecture…

From policy triage we conclude that not everything can be standardized or defined. The points of leverage must be discerned and the architect's resources applied sparingly."

-Mark S. Maier, INCOSE Fellow

Source:
Maier, Mark W. "Architecting Principles for Systems-of-Systems." *Systems Engineering*, vol. 1, no. 4, 1998, pp. 267–284., doi:10.1002/(sici)1520-6858(1998)1:43.0.co;2-d.

Resilience as function of network topology: how to model?

1. Identify networked architectural property as proxy for resilience
2. Identify leverage points to achieve architectural property
3. Manipulate leverage points to realize architectural property

"From stable intermediate forms we conclude that the interfaces must support severability... the ability to remove or add a physical component…

From ensuring collaboration we conclude that attention must be paid to how the participating components derive value from participation."

-Mark S. Maier

Source:
Maier, Mark W. "Architecting Principles for Systems-of-Systems." *Systems Engineering*, vol. 1, no. 4, 1998, pp. 267–284., doi:10.1002/(sici)1520-6858(1998)1:43.0.co;2-d.

Resilience as function of network topology: how to model?

1. Identify networked architectural property as proxy for resilience
2. Identify leverage points to achieve architectural property
3. Manipulate leverage points to realize architectural property
4. Measure level of realized increase

> “The overarching consideration is architecture as communications.”
>
> -Mark S. Maier

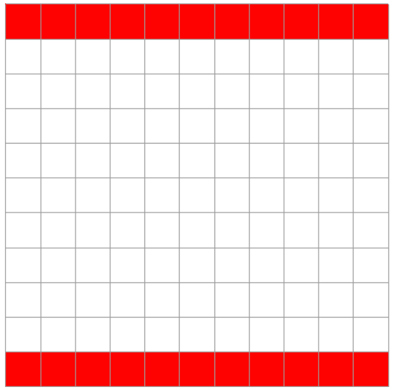
Source:
Maier, Mark W. “Architecting Principles for Systems-of-Systems.” *Systems Engineering*, vol. 1, no. 4, 1998, pp. 267–284., doi:10.1002/(sici)1520-6858(1998)1:43.0.co;2-d.

Resilience as function of network topology: how to model?

1. Identify networked architectural property as proxy for resilience
2. Identify leverage points to achieve architectural property
3. Manipulate leverage points to realize architectural property
4. Measure level of realized increase
5. Simulate effect of increase on network performance

Source:
Maier, Mark W. “Architecting Principles for Systems-of-Systems.” *Systems Engineering*, vol. 1, no. 4, 1998, pp. 267–284., doi:10.1002/(sici)1520-6858(1998)1:43.0.co;2-d.

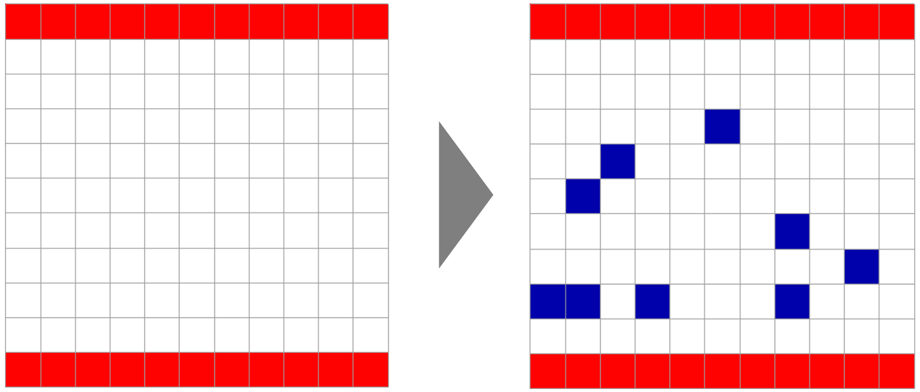
Connectivity phase change on a square lattice



Fluid at top/bottom seeks to percolate through porous medium, e.g. filtration of water through soil or coffee grounds.

Source Code:
"Percolation on a Square Grid" from the Wolfram Demonstrations Project
http://demonstrations.wolfram.com/PercolationOnASquareGrid/
Contributed by: Stephen Wolfram

Connectivity phase change on a square lattice



Fluid at top/bottom seeks to percolate through porous medium, e.g. filtration of water through soil or coffee grounds.

At occupation probability p=.1, isolated clusters appear in blue, showing presence of unconnected ‘pores’.

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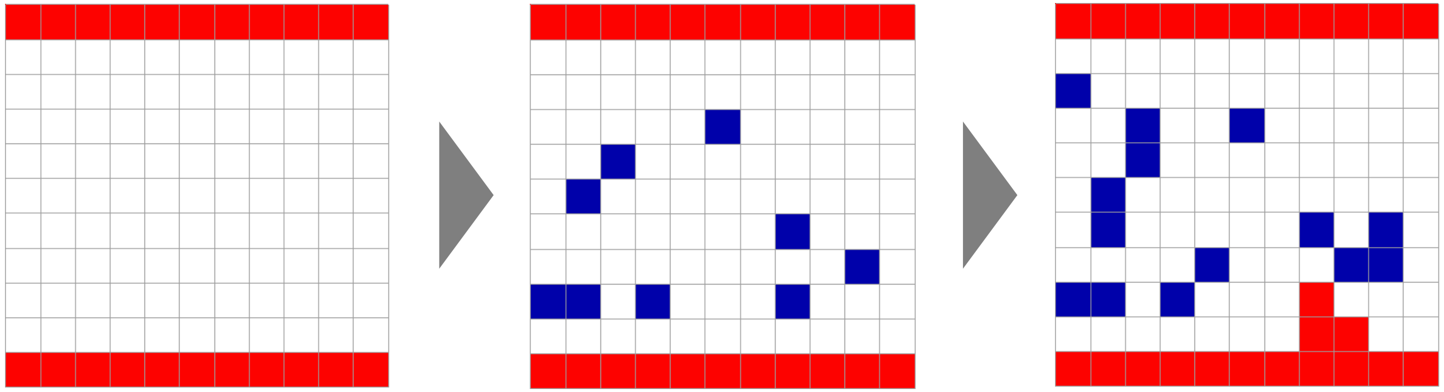
Connectivity phase change on a square lattice



Fluid at top/bottom seeks to percolate through porous medium, e.g. filtration of water through soil or coffee grounds.

At occupation probability p=.1, isolated clusters appear in blue, showing presence of unconnected 'pores'.

At p=.2, some clusters connect to top/bottom of porous medium, but none span, and no large clusters occur.

Source Code:
"Percolation on a Square Grid" from the Wolfram Demonstrations Project
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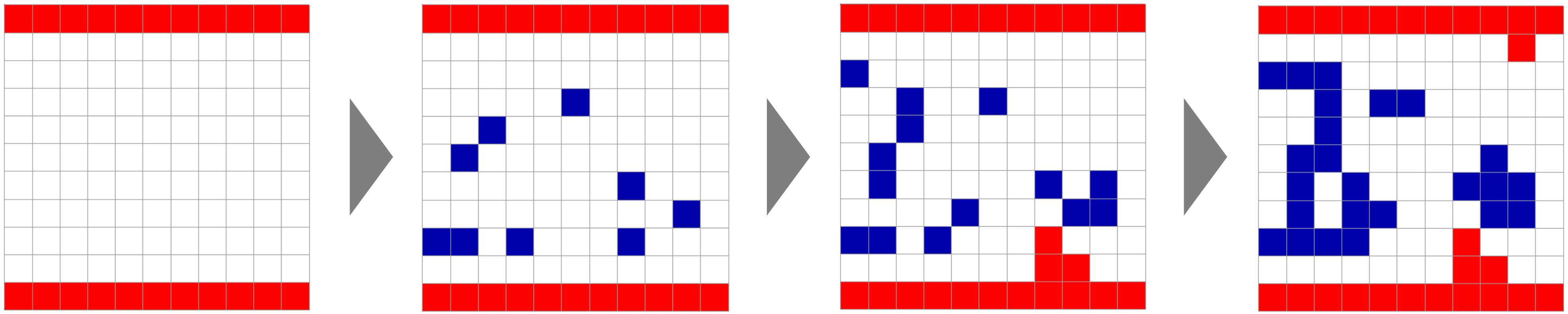
Connectivity phase change on a square lattice



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At p=.3, multiple large connected clusters emerge, but do not span. Tipping point towards connectivity is imminent.

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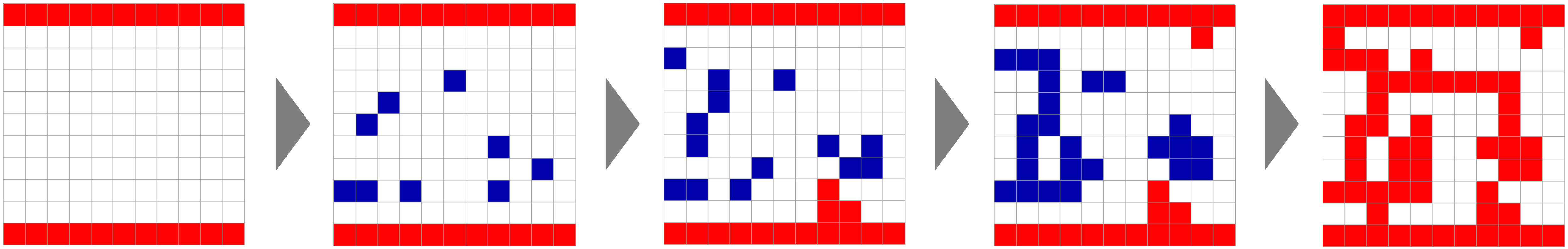
Connectivity phase change on a square lattice



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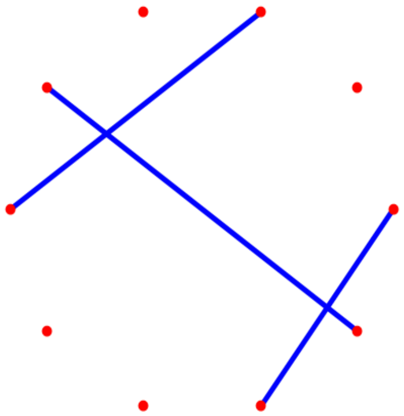
At p=.3, multiple large connected clusters emerge, but do not span. Tipping point towards connectivity is imminent.

At p =.4, percolation threshold is passed, and phase transition occurs. Every occupied point on lattice is connected.

Source Code:
"Percolation on a Square Grid" from the Wolfram Demonstrations Project
http://demonstrations.wolfram.com/PercolationOnASquareGrid/
Contributed by: Stephen Wolfram

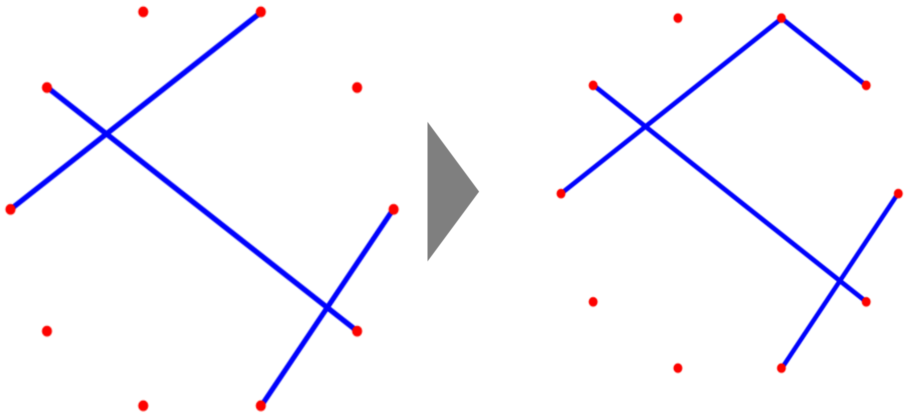
Connectivity phase change on a network



In a random network of 10 nodes, 45 edges [n(n-1)/2)] are possible. Here, there are 3 edges and 3 unconnected clusters.

Source Code:
"Connectivity-Based Phase Transition"
http://demonstrations.wolfram.com/ConnectivityBasedPhaseTransition/ Wolfram Demonstrations Project Published: September 20, 2011
Contributed by: Mark D. Normand

Connectivity phase change on a network

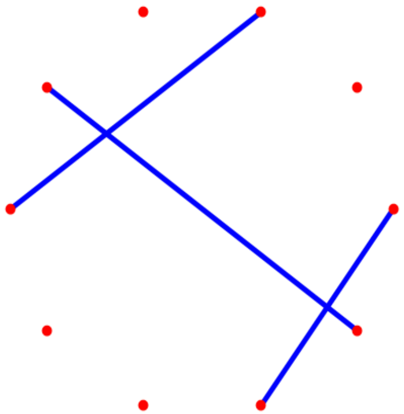


In a random network of 10 nodes, 45 edges [n(n-1)/2)] are possible. Here, there are 3 edges and 3 unconnected clusters.

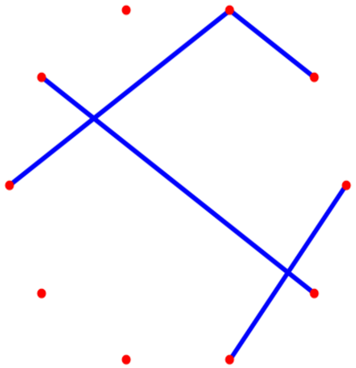
With 4 edges, there are still only 3 unconnected clusters, and largest has only 3 nodes.

Source Code:
"Connectivity-Based Phase Transition"
http://demonstrations.wolfram.com/ConnectivityBasedPhaseTransition/ Wolfram Demonstrations Project Published: September 20, 2011
Contributed by: Mark D. Normand

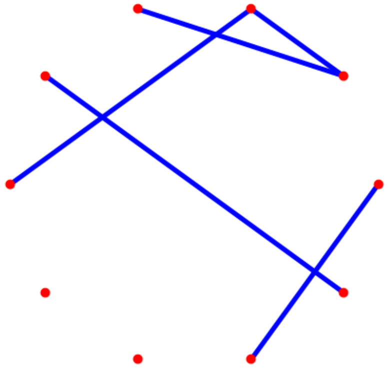
Connectivity phase change on a network



In a random network of 10 nodes, 45 edges [n(n-1)/2)] are possible. Here, there are 3 edges and 3 unconnected clusters.



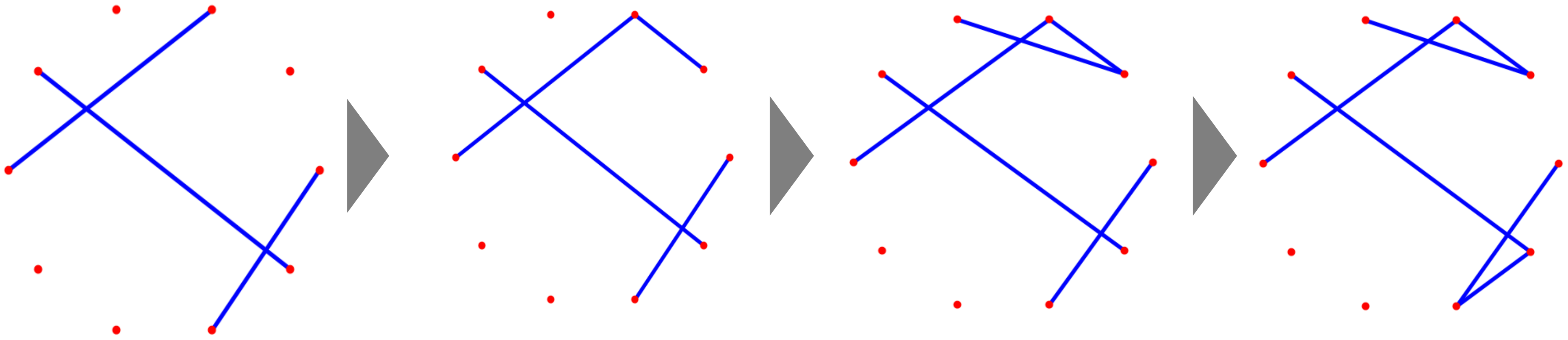
With 4 edges, there are still only 3 unconnected clusters, and largest has only 3 nodes.



With 5 edges, still only 3 clusters, but largest now connects 4 nodes (note: different finite random networks will behave differently).

Source Code:
"Connectivity-Based Phase Transition"
http://demonstrations.wolfram.com/ConnectivityBasedPhaseTransition/ Wolfram Demonstrations Project Published: September 20, 2011
Contributed by: Mark D. Normand

Connectivity phase change on a network



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With 6 edges, two connected clusters emerge, of 4 nodes each. Network is broken into halves, neither communicating.

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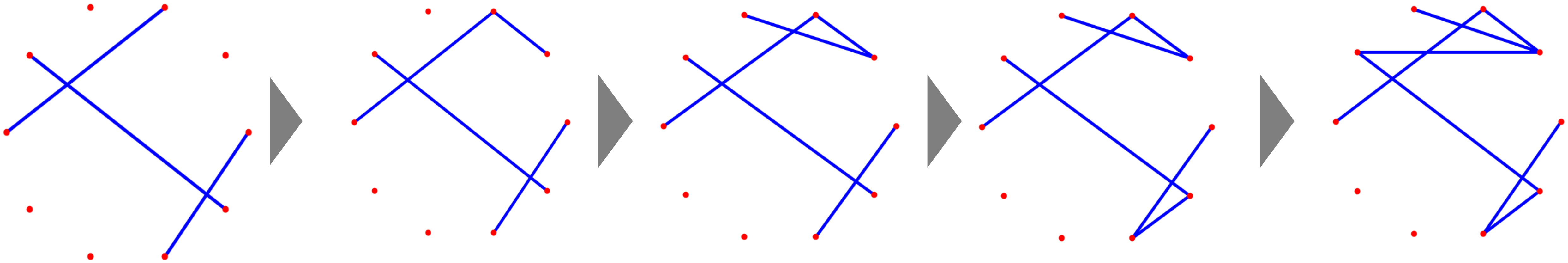

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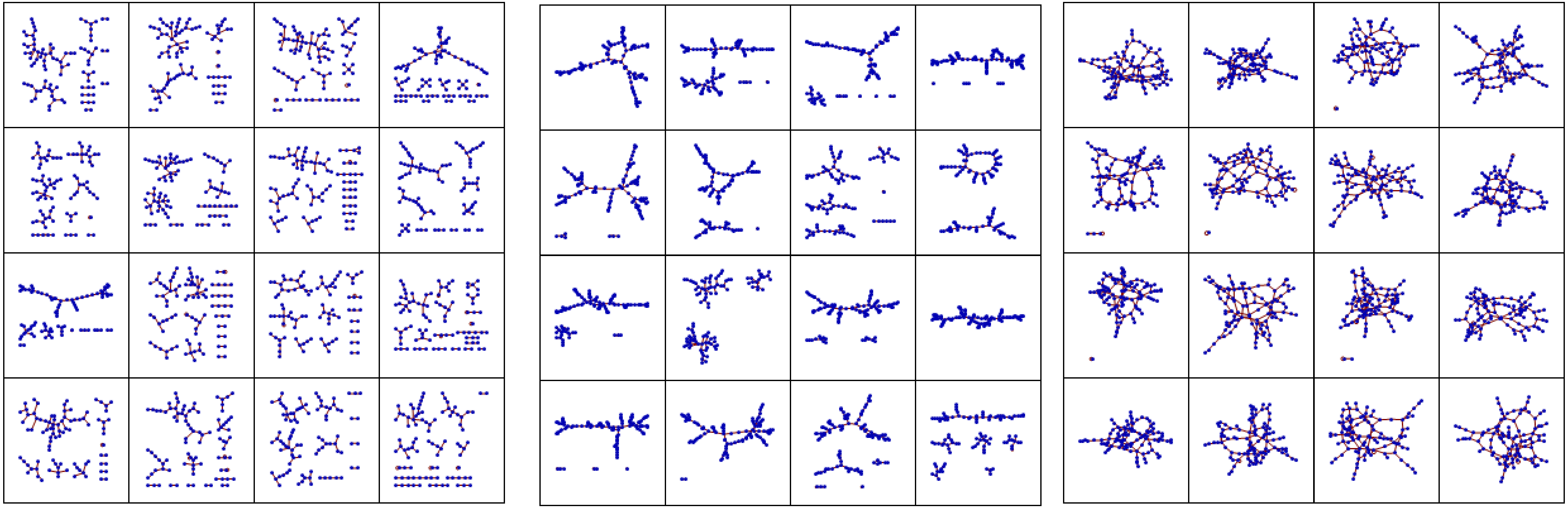
With 5 edges, still only 3 clusters, but largest now connects 4 nodes (note: different finite random networks will behave differently).

With 6 edges, two connected clusters emerge, of 4 nodes each. Network is broken into halves, neither communicating.

With 7 edges, network ‘tips’ into connectivity, with largest cluster having 8 out of 10 possible nodes (note: network percolation ≠ all terminal connectivity)

Source Code:
"Connectivity-Based Phase Transition"
http://demonstrations.wolfram.com/ConnectivityBasedPhaseTransition/ Wolfram Demonstrations Project Published: September 20, 2011
Contributed by: Mark D. Normand

Connectivity phase changes in random networks



Three arrays of 100-node Erdos-Renyi Poisson random graphs shown, with .8, 1., and 1.2 edges per node, respectively. In the limit of large N, Erdos showed that phase change occurs when average degree of nodes = 1, as shown in middle array. Below that level, graphs are disconnected; above that, connected. At average degree = 1, results are mixed. Note: these regularities do not apply exactly to smaller, finite graphs, as encountered in the real world.

Source Code:
"Samples of Random Graphs" from the Wolfram Demonstrations Project
http://demonstrations.wolfram.com/SamplesOfRandomGraphs/
Contributed by: Stephen Wolfram

Calculating clustering and degree correlation in R

```
> library(igraph)
> vertices=20
> edges=50
> ergraph<-sample_gnm(vertices,edges,directed = FALSE, loops =FALSE)
>
> root_node<-NA
> intermediate_node<-NA
> final_node<-NA
> root_node_degree<-NA
> neighbor_node_degree<-NA
> open_triangle<-NA
> closed_triangle<-NA
> counter=0
> counter2=0
> for (i in 1:vertices) {
+   for (j in (1:length(as_ids(neighbors(ergraph,i))))){
+     counter=counter+1
+     root_node_degree[counter]=degree(ergraph,i)
+     neighbor_node_degree[counter]=degree(ergraph,as_ids(neighbors(ergraph,i))[j])
+     for (k in (1:length(as_ids(neighbors(ergraph,as_ids(neighbors(ergraph,i))[j]))))){
+       counter2=counter2 + 1
+       root_node[counter2]=i
+       intermediate_node[counter2]=as_ids(neighbors(ergraph,i))[j]
+       final_node[counter2]=as_ids(neighbors(ergraph,intermediate_node[counter2]))[k]
+       if (i==final_node[counter2]){
+         open_triangle[counter2]=0
+         closed_triangle[counter2]=0}
+       else if (are.connected(ergraph,i,final_node[counter2])){
+         open_triangle[counter2]=0
+         closed_triangle[counter2]=1}
+       else {
+         open_triangle[counter2]=1
+         closed_triangle[counter2]=0}
+     }}}
```

```
> sum(closed_triangle)/(sum(open_triangle)+sum(closed_triangle))
[1] 0.2288136
> transitivity(ergraph)
[1] 0.2288136
>
> cor(root_node_degree,neighbor_node_degree)
[1] -0.1408083
> assortativity_degree(ergraph)
[1] -0.1408083
```

Source Code:
Csardi G, Nepusz T: The igraph software package for complex network research, InterJournal, Complex Systems 1695. 2006
Igraph.org

Estimates of connectivity phase change thresholds in R

```
> library(igraph)
> vertices=1000
> edges=2500
> ergraph<-sample_gnm(vertices,edges,directed = FALSE, loops =FALSE)
> A<-as_adjacency_matrix(ergraph)
> A_eigen<-eigen(A, symmetric = TRUE,only.values=TRUE)[1]
> p_bar<-1/max(A_eigen$values)
> p_bar
[1] 0.1622749
```

For dense matrices, can use inverse of leading eigenvalue of adjacency matrix, as extracted from DSM [due to Bollobas]

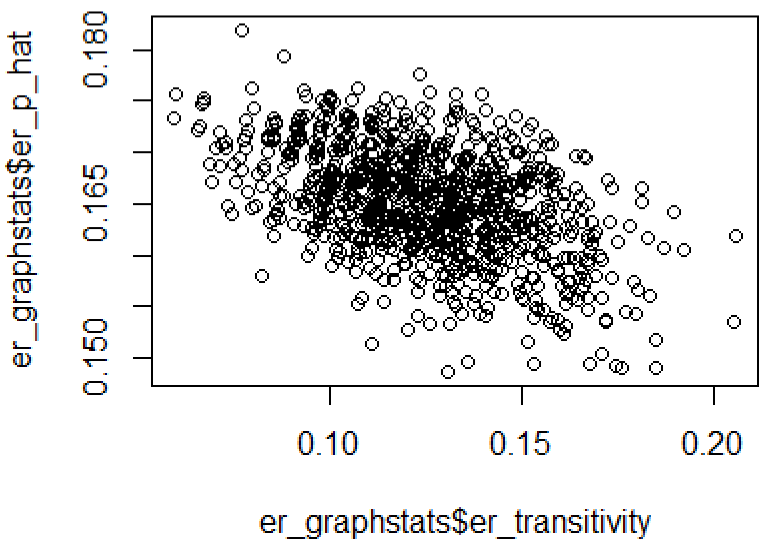
For sparse matrices, use inverse of leading eigenvalue of Hashimoto nonbacktracking matrix [due to Newman et al], also extracted from DSM (most DSM's are sparse).

```
> library(igraph)
> vertices=1000
> edges=2500
> ergraph<-sample_gnm(vertices,edges,directed = FALSE, loops =FALSE)
> A<-as_adjacency_matrix(ergraph)
> A_eigen<-eigen(A, symmetric = TRUE,only.values=TRUE)[1]
> I<-diag(vertices)
> D<-diag(degree(ergraph))
> B<-I-D
> Z<-matrix(0,nrow=vertices,ncol=vertices)
> H<-rbind(cbind(A,B),cbind(I,Z))
> H_eigen<-eigen(H, symmetric = TRUE,only.values=TRUE)[1]
> p_hat<-1/max(H_eigen$values)
> p_hat
[1] 0.1584883
```

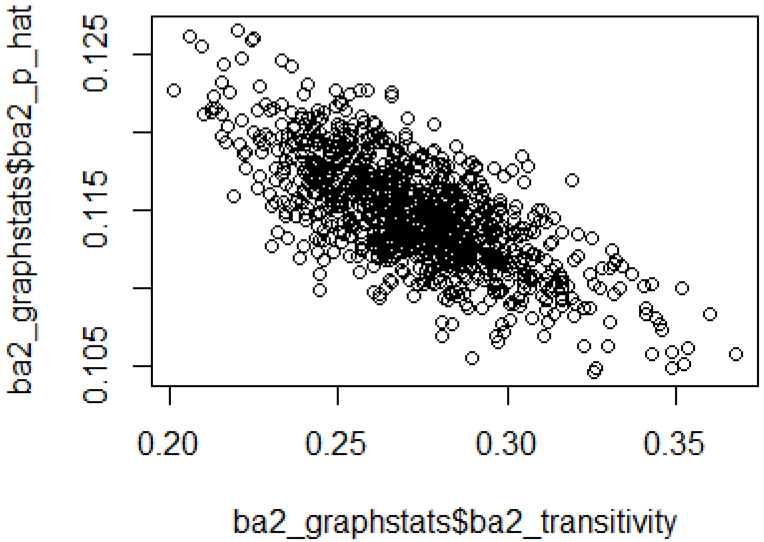
Source:
Radicchi, Filippo. "Predicting Percolation Thresholds in Networks." *Physical Review E*, vol. 91, no. 1, 2015, doi:10.1103/physreve.91.010801.

Main Findings I:
Clustering strongly correlates with increased network resilience, generally, lowering tipping point into connectivity

Erdos-Renyi Random Graphs

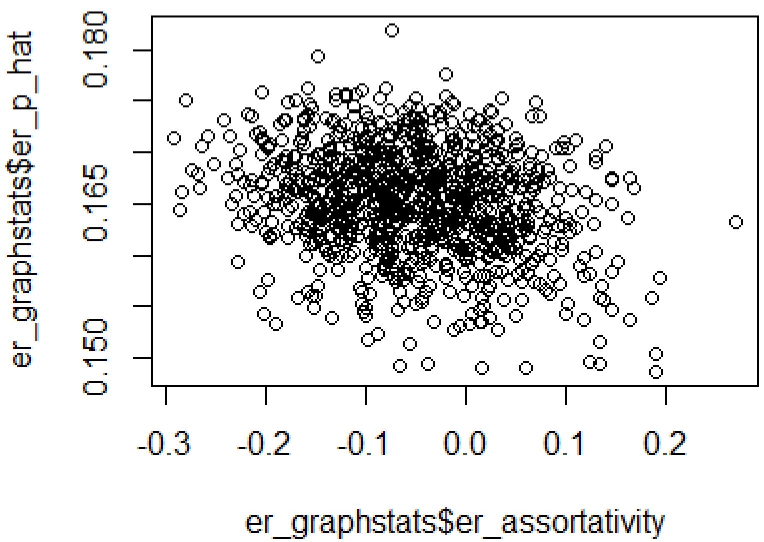


Barabasi-Albert Scale-Free Graphs, k=2

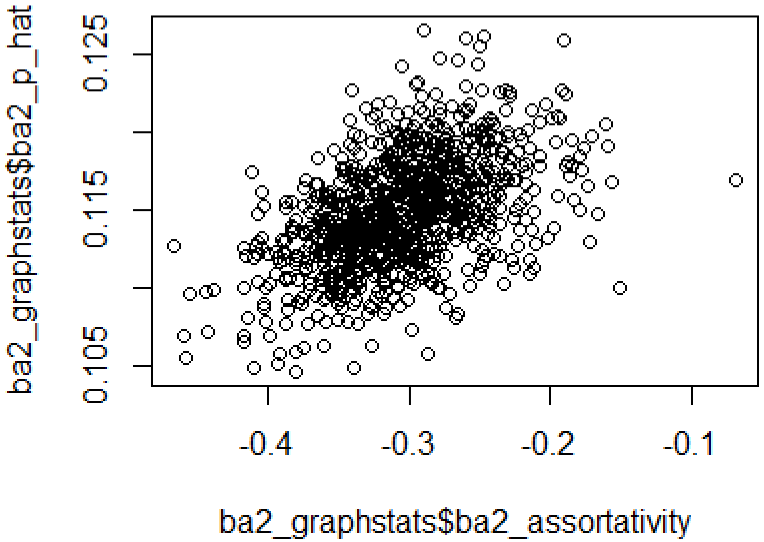


Main Findings II: Degree correlation has weaker, mixed association with increased network resilience, generally.

Erdos-Renyi Random Graphs

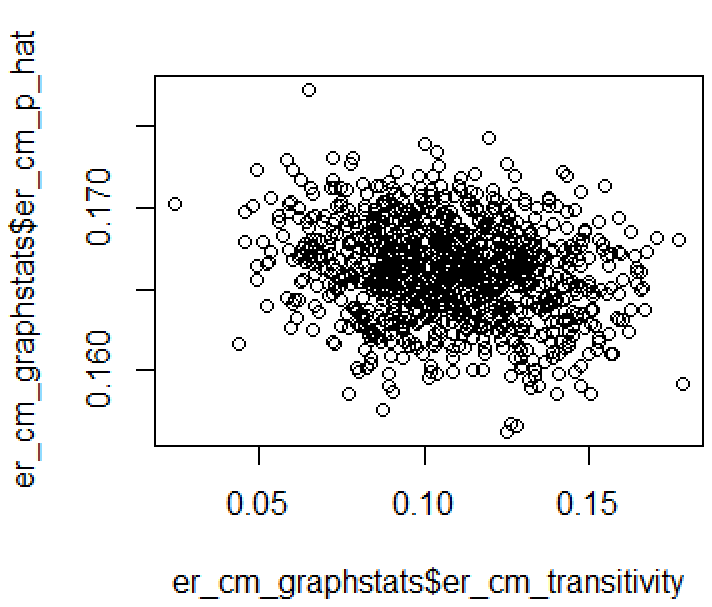


Barabasi-Albert Scale-Free Graphs, k=2

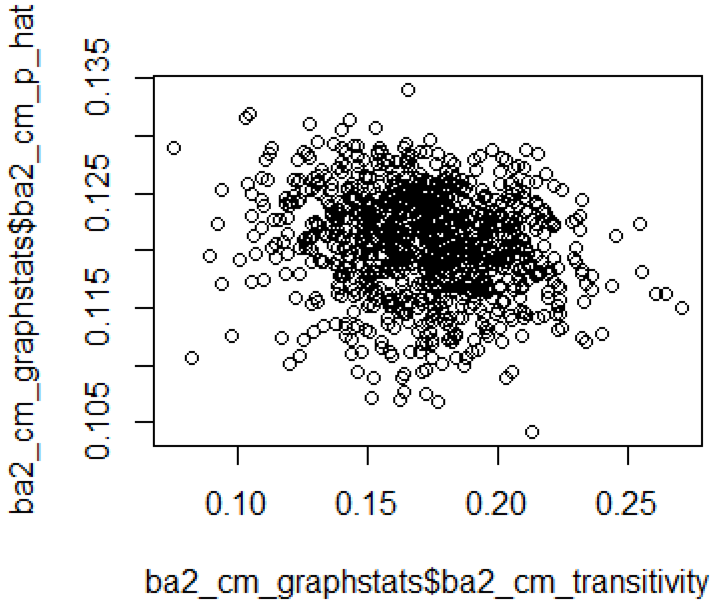


Main Findings III:
In contrast, clustering has almost no correlation with increased network resilience when keeping node degree constant, under the ‘configuration model’.

Erdos-Renyi Random Graphs

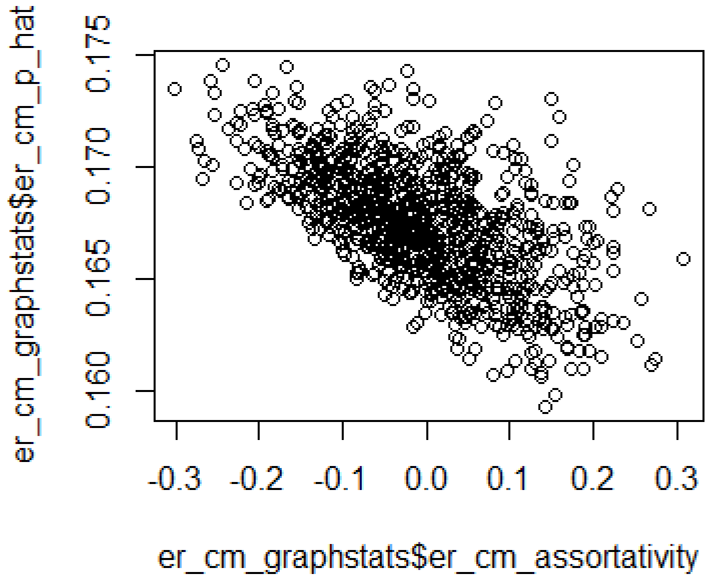


Barabasi-Albert Scale-Free Graphs, k=2

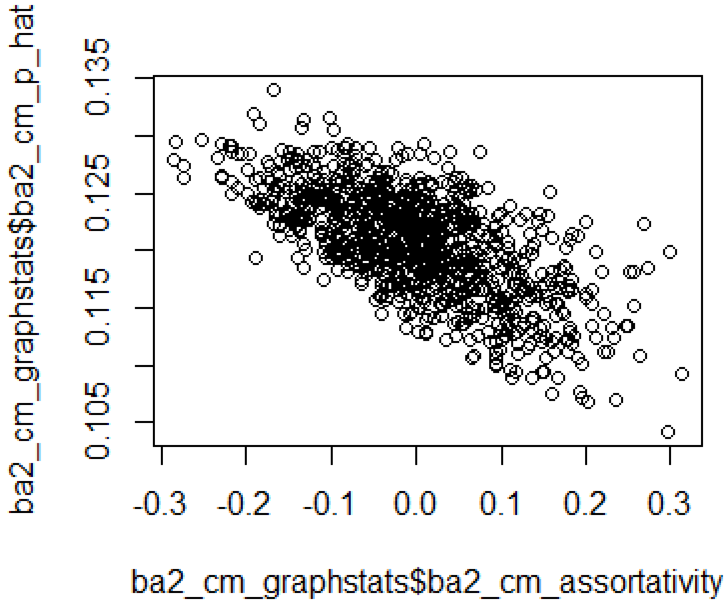


Main Findings IV:
Meanwhile, degree correlation has strong association with increased network resilience when keeping node degree constant, under the ‘configuration model’.

Erdos-Renyi Random Graphs



Barabasi-Albert Scale-Free Graphs, k=2



Main findings V:

Using the regularities observed above as heuristics, edge addition and rewiring rules can be derived. A consistent improvement of ~2% across all graph types is observed, between single ‘good’ and ‘bad’ edge additions / rewirings.

Effect of single worst rewiring, keeping degree distribution constant, on connectivity threshold.

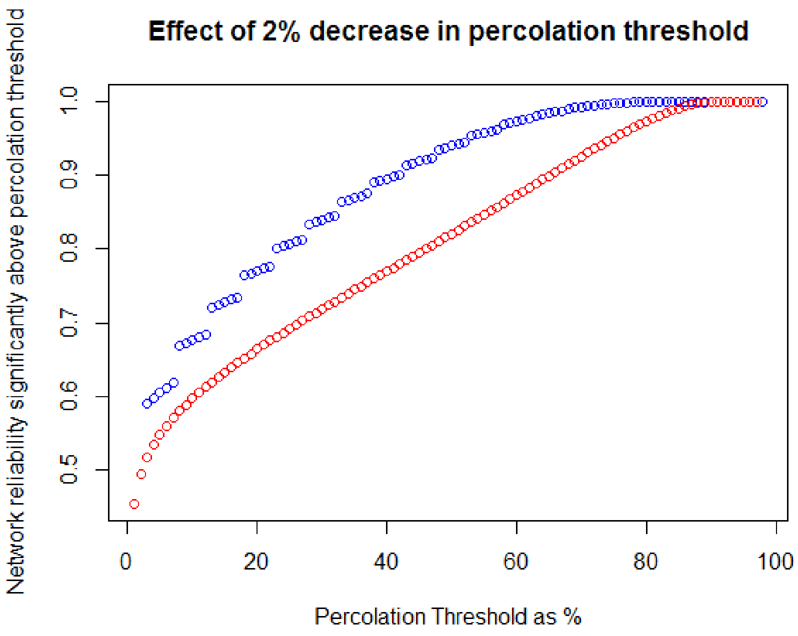
Effect of single best rewiring, keeping degree distribution constant, to maximally increase node degree correlation, on connectivity threshold.

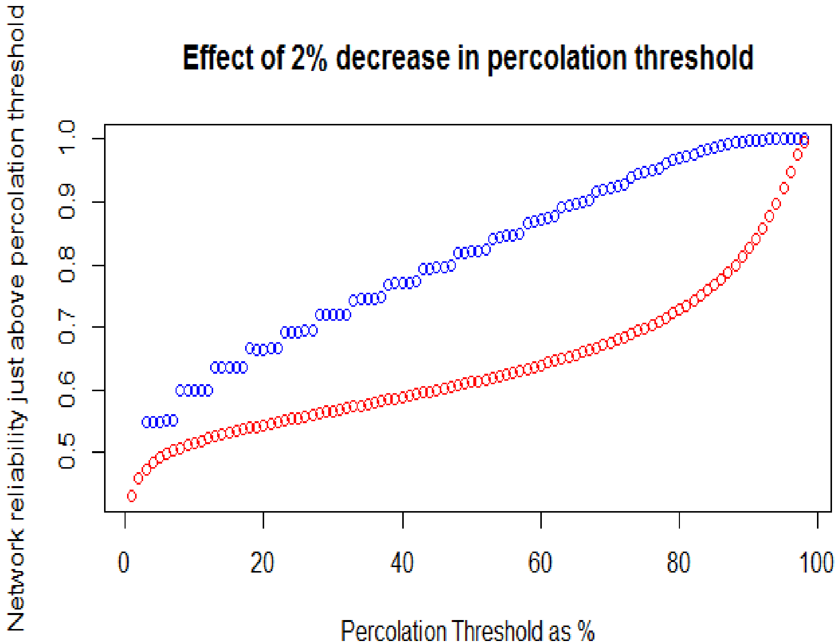
Effect of adding single best edge to network, to maximally increase network clustering coefficient, on connectivity threshold.

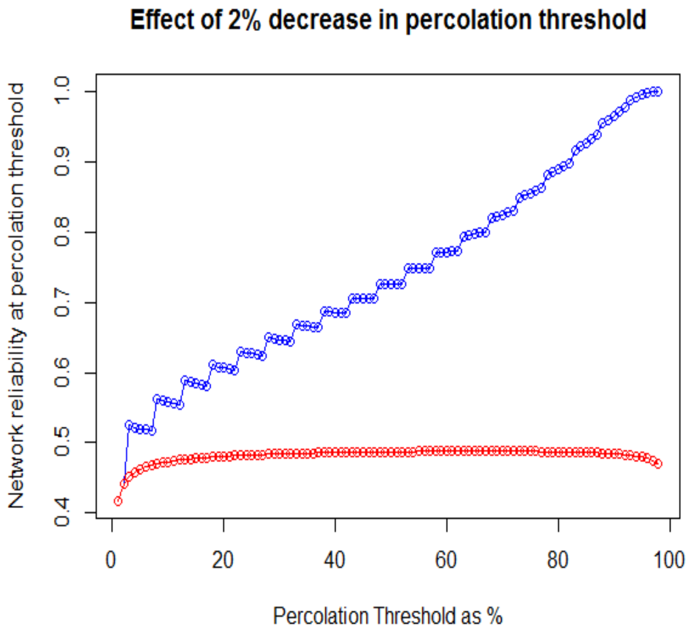
Effect of adding single bad edge, completing as few triangles as possible.

Effects of 2% decrease in percolation threshold

This effect is especially relevant when the system is performing (in terms of uniform node reliability) at or near the connectivity threshold. Overall network reliability calculations when system is performing comfortably above (3%), just above (1%) and at the percolation threshold, over a range of different thresholds, are as follows (improved network's performance is in blue):







Conclusions

Resilience can be modeled as an architectural property of networks

Viewing architecture as communication, a network’s adaptive capacity to restore communications, after failure, is key

That capacity is best modeled via the notion of percolation threshold

For socio-technical networks, leverage points are both necessary and useful

Clustering (percent completed triangles) and homophily (node degree correlation) are best leverage points

The Design Structure Matrix is a key tool in deploying node addition and rewiring rules

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Material here has been abstracted, summarized, or developed from a dissertation to be submitted to the George Washington University in partial fulfillment of the requirements for the Ph.D. in System Engineering.