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Understanding System Interdependence to Improve Resilience of Shipboard Cyber Physical Systems

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Abstract

Modern critical infrastructures are made with Cyber-Physical Systems (CPS) with components/subsystem interdependencies intended to make the entire system/infrastructure more robust. Vulnerabilities, such as random failures and cyber-attacks can result in cascading system failures due to network dependencies. A significant knowledge gap exists in understanding these interdependencies and its influence on system design and system resilience. While numerous studies have explored the resilience of interdependent network, a method to analyze and model such vulnerabilities has yet to be defined. The proposed methodology optimizes a transportation system design by quantifying the modeled system's performance (i.e. Measure of Performance (MOP)) and effectiveness (i.e. Measure of Effectiveness (MOE)) by looking at the network failure using inverse percolation theory. Inverse percolation theory models the network failure by removing fractions of the nodes or edges resulting in network transitioning from functional network to non-functional network. Using a comprehensive approach, the author analyzes a maritime system network resiliency in three phases: 1) Develop a network model using real data from a future shipboard system's interface connections (nodes and edges) to determine its characteristics and fragmentation threshold. 2) Compare features from a legacy model with a proposed model and describe inherent vulnerabilities among models using an Erdos-Renyi and Scale Free. 3) Simulate the removal of nodes or links to determine the optimal system performance and fragmentation threshold to increase the system's MOP => 0.65 and reduce significant system risk.

Keywords: Resilience, interdependence, CPS, percolation, simulation.

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9.3% of 2013 U.S. GDP* was supported by the Transportation Sector

Approx. 6% of the 2013 U.S. Employed Population** worked in the Transportation Sector

Approx. 19.6 Billions of Tons of Goods*** were shipped in 2014

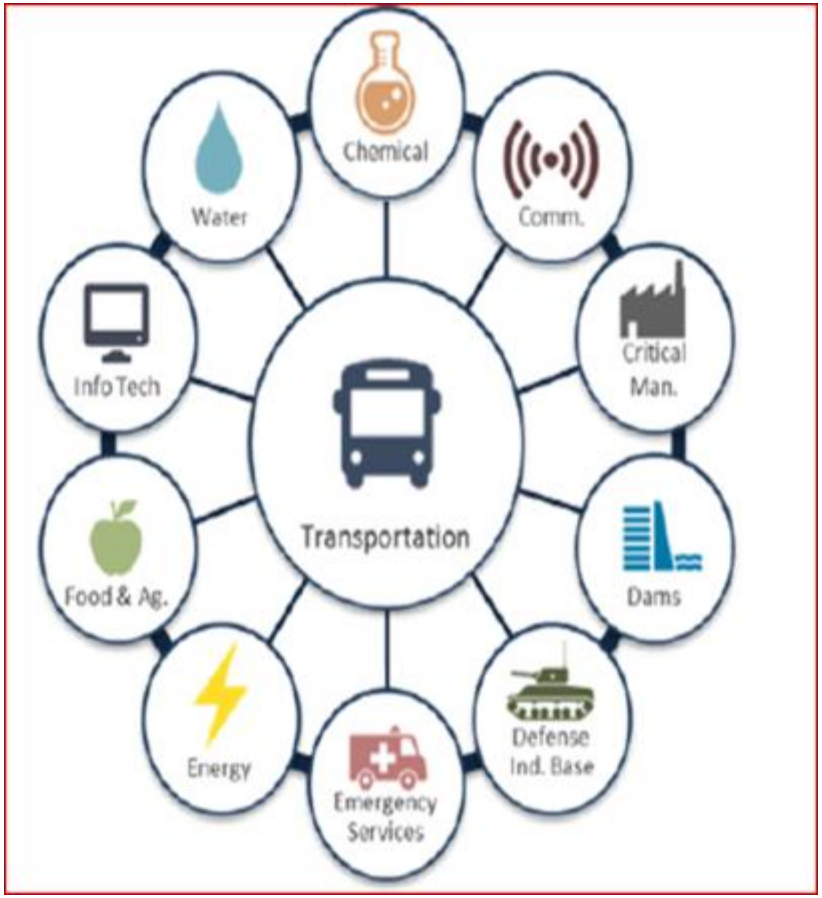

Figure 1. Transportation Cross-Sector Dependencies ((https://www.dhs.gov)

Thesis Statement

- The Transportation network CPS interdependencies affects the system's resilience due to direct and indirect links between systems.

Research Question

- Does the CPS interdependencies improve the Transportation systems' resilience after a disruption?"

Hypothesis

- ***Null Hypothesis (Ho)***: The Transportation system CPS interdependencies decrease system resilience.
- **Alternative Hypothesis (Ha)**: The Transportation system CPS interdependencies increase system resilience.

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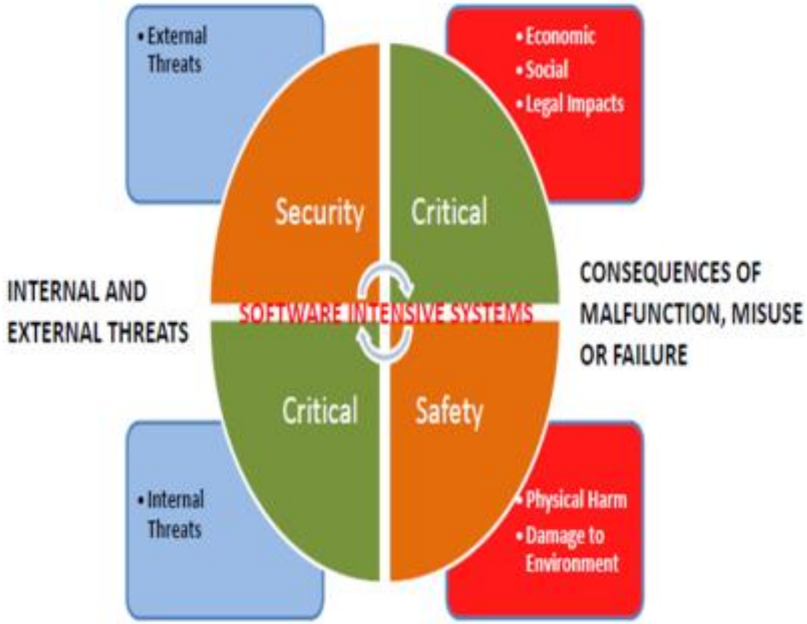
SYSTEMS OF SYSTEMS AND CYBER PHYSICAL SYSTEMS



COMPUTATIONAL AND PHYSICAL COMPONENTS FOR CYBER PHYSICAL SYSTEMS		
	RESOURCES	
COMPONENTS	*Computational Systems*	*Physical Systems*
Cyber Systems	Data Processing	Supporting Hardware
Physical Systems	SCADA	Mechanical Devices

Definitions

- **Interdependency** -A bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other (physical, cyber, geographic, logical).
- **System of Systems**. A system is a combination of interacting elements organized to achieve one or more stated purpose (INCOSE).
- **Cyber-Physical System (CPS)**. Refers to the tight conjoining of and coordination between computational and physical resources (NSF).
- **Resilience**. Refers to the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies (DHS).
- **Cascading Failure**. Defined as successive interdependent component failures in a system.

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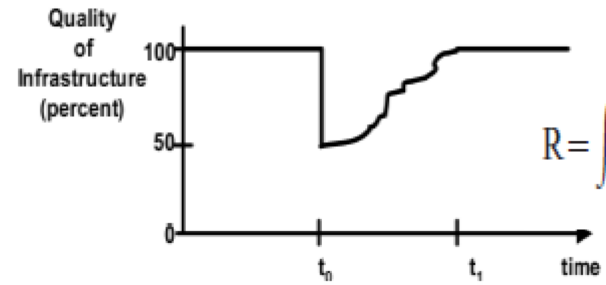
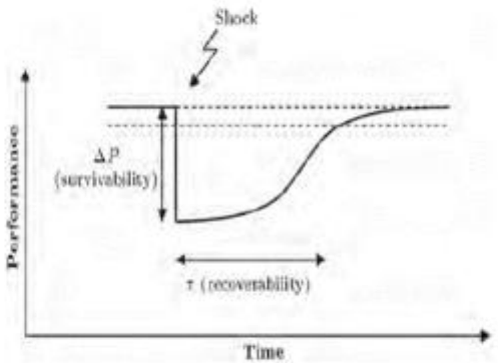
- **Reliability**. Ability of a system to perform required functions under stated conditions for a specified period of time.
- **Robustness**. System property that allows to satisfy a fixed set of requirements despite changes in the environment or within the system.
- **Redundancy**. Systems elements exist that are substitutable and capable of satisfying function.
- **Resourcefulness**. The capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt the system.
- **Rapidity.** The capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

Measure of Resilience

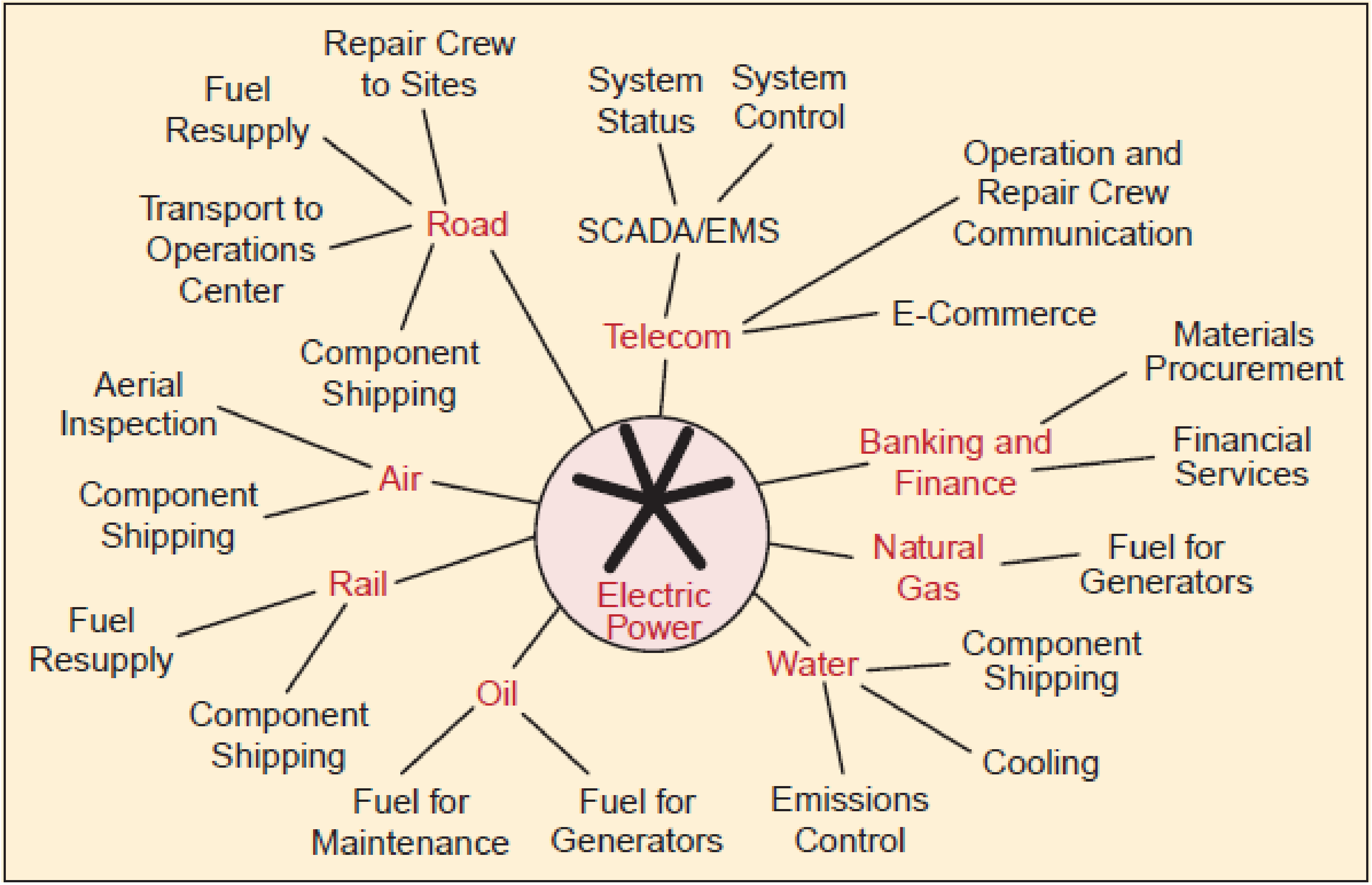


$$R = \int_{t_0}^{t_1} [100 - Q(t)]dt$$

Survivability vs. Recoverability



Example of Infrastructure Interdependencies



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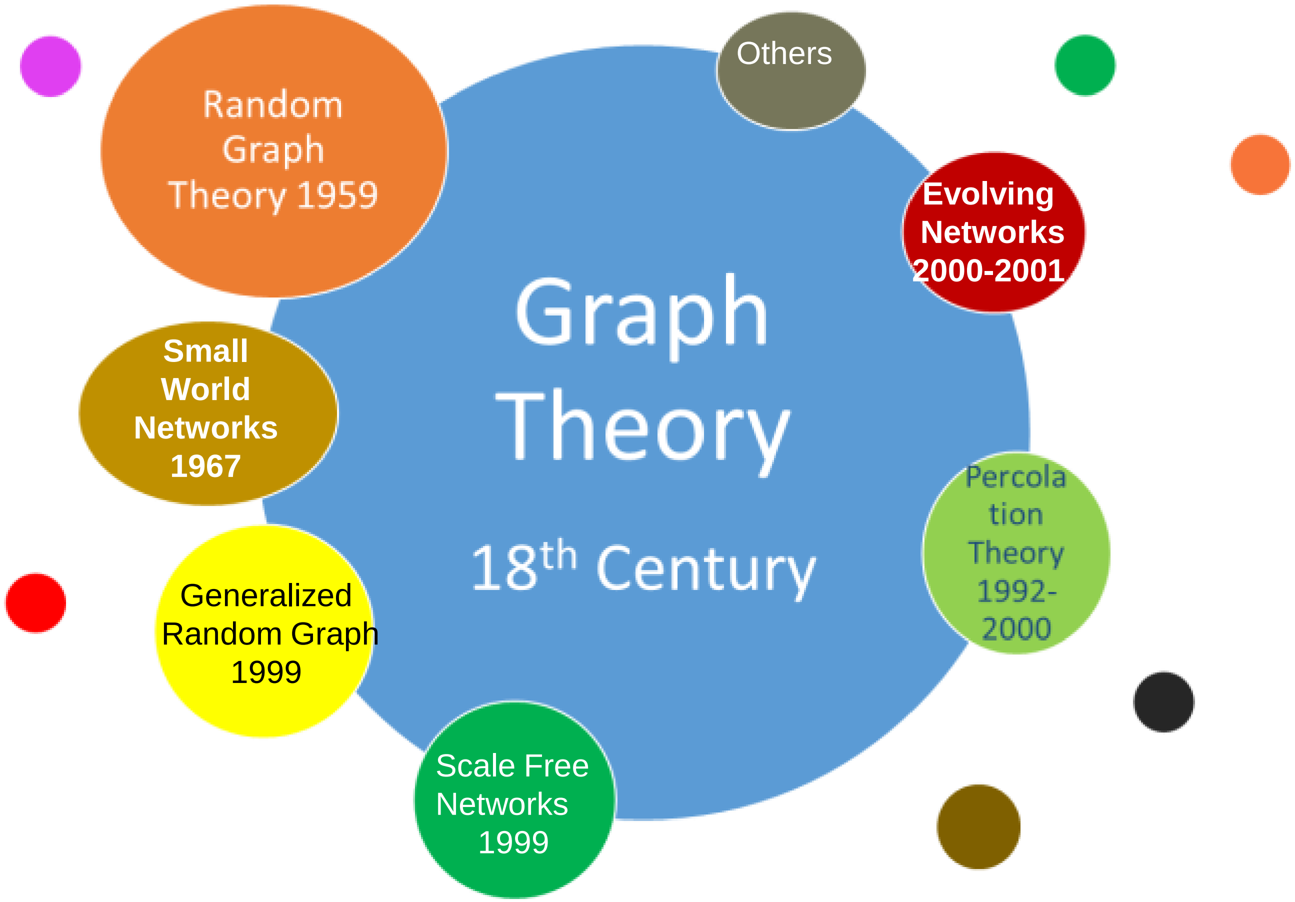
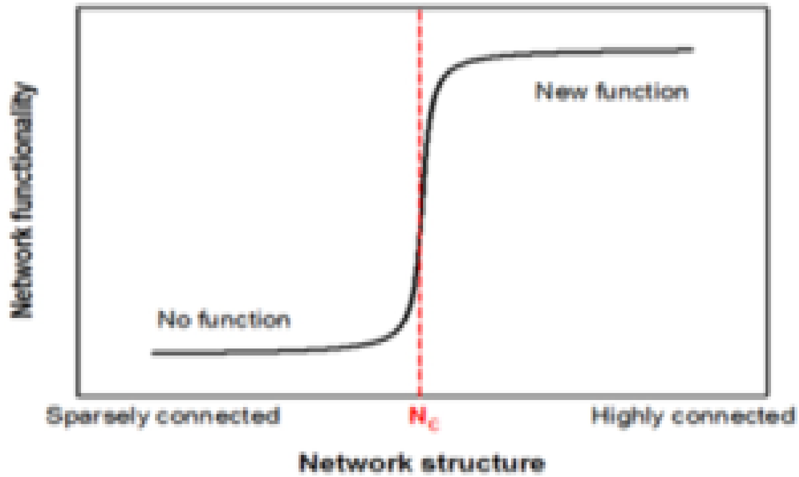

Random Graph Theory 1959
Others
Evolving Networks 2000-2001
Graph Theory
18th Century
Small World Networks 1967
Percola tion Theory 1992-2000
Generalized Random Graph 1999
Scale Free Networks 1999

Percolation Theory



Resiliency Models

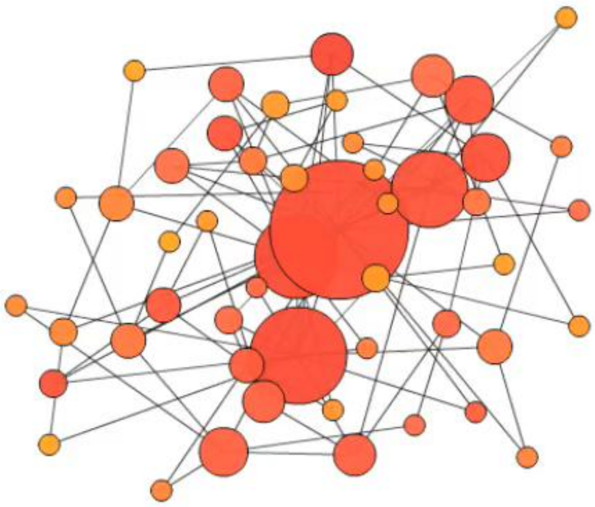
- ❑ Albert, Jeong and Barabasi (2000)
- ❑ Cohen, Erez, ben-Avraham, Havlin (2000)
- ❑ Callaway, Newman, Strogatz, Watts (2000)

•< pc , no clustering
•> pc, clustering
•Test for network robustness

Resilience = function (Robustness, Redundancy, Resourcefulness, Rapidity)

- ❑ Robustness can be explained by percolation theory.
- ❑ Redundancy can be explained by reliability theory.
- ❑ Resourcefulness can be explained by availability and maintainability.
- ❑ Rapidity can be explained by system performance metrics.

Scale-Free Network Under Node Failures Using Inverse Percolation



How does the interdependent structure affect system's resilience?

Reference: Barabasi, Network Science, Video 8.1

Inverse Percolation Theory

Sample problem: What are the consequences of removing a fraction (f) of all nodes during a random cyber attack on shipboard network? At what threshold (fc) will the shipboard network fall apart (no giant component)?

Random node removal changes the following:

a. Degree of individual nodes k. $P(k) = ck^{-\alpha}$

b. Degree distribution P(k).

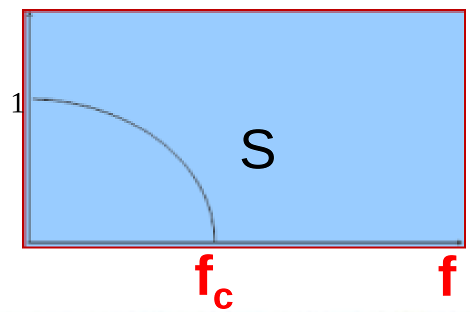
A node with degree k will loose some links and become a node with degree k' with probability: $\binom{k}{k'} f^{k-k'}(1-f)^{k'} \quad k' \le k$

The new distribution is: $P'(k') = \sum_{k=k'}^{\infty} P(k) \binom{k}{k'} f^{k-k'}(1-f)^{k'}$

- k>2 : giant cluster exist
- k<2 : many disconnected clusters

Resilience

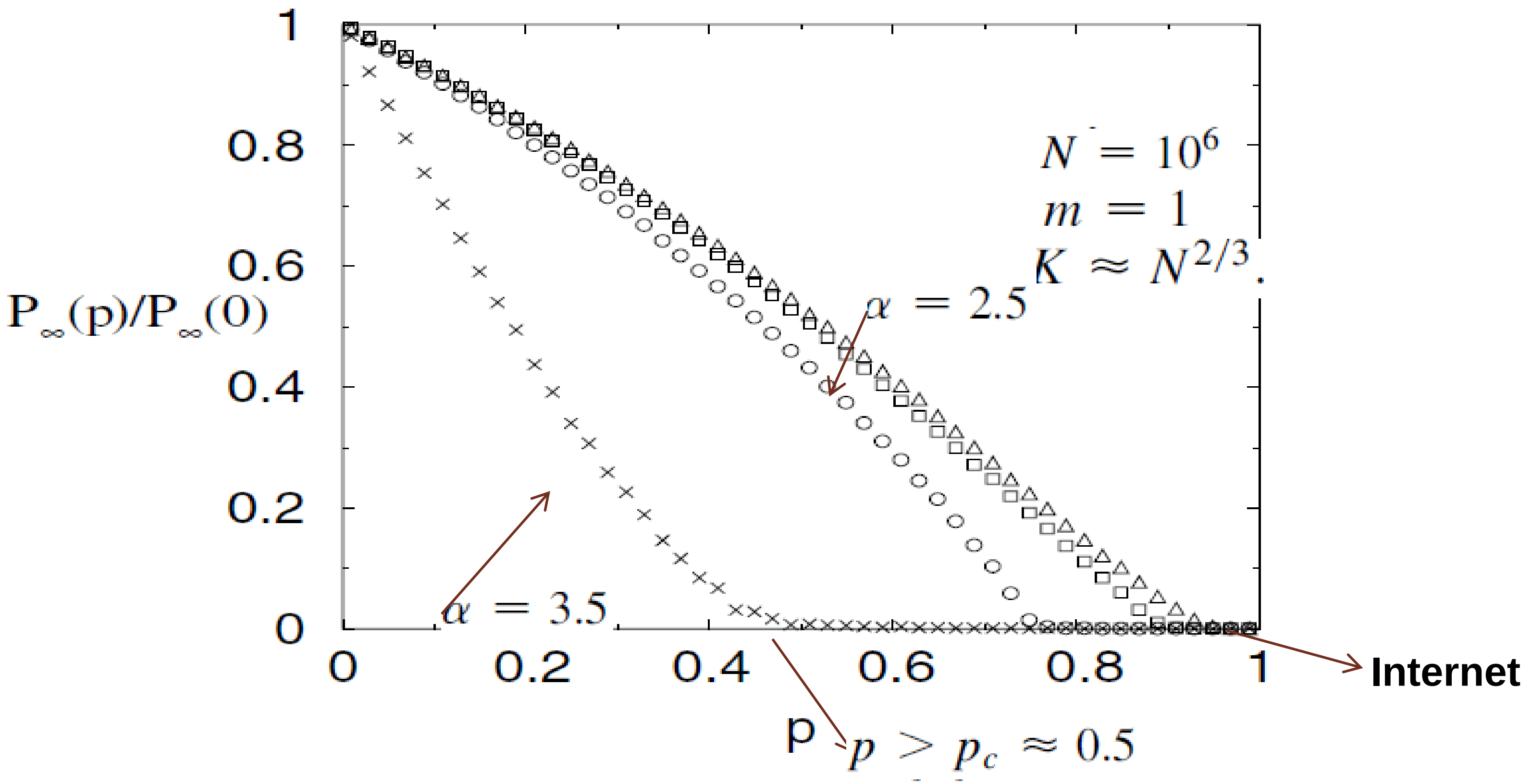
$$P_c = 1 - f_c = \frac{<k>}{<k^2> - <k>}$$



Fragmentation Threshold

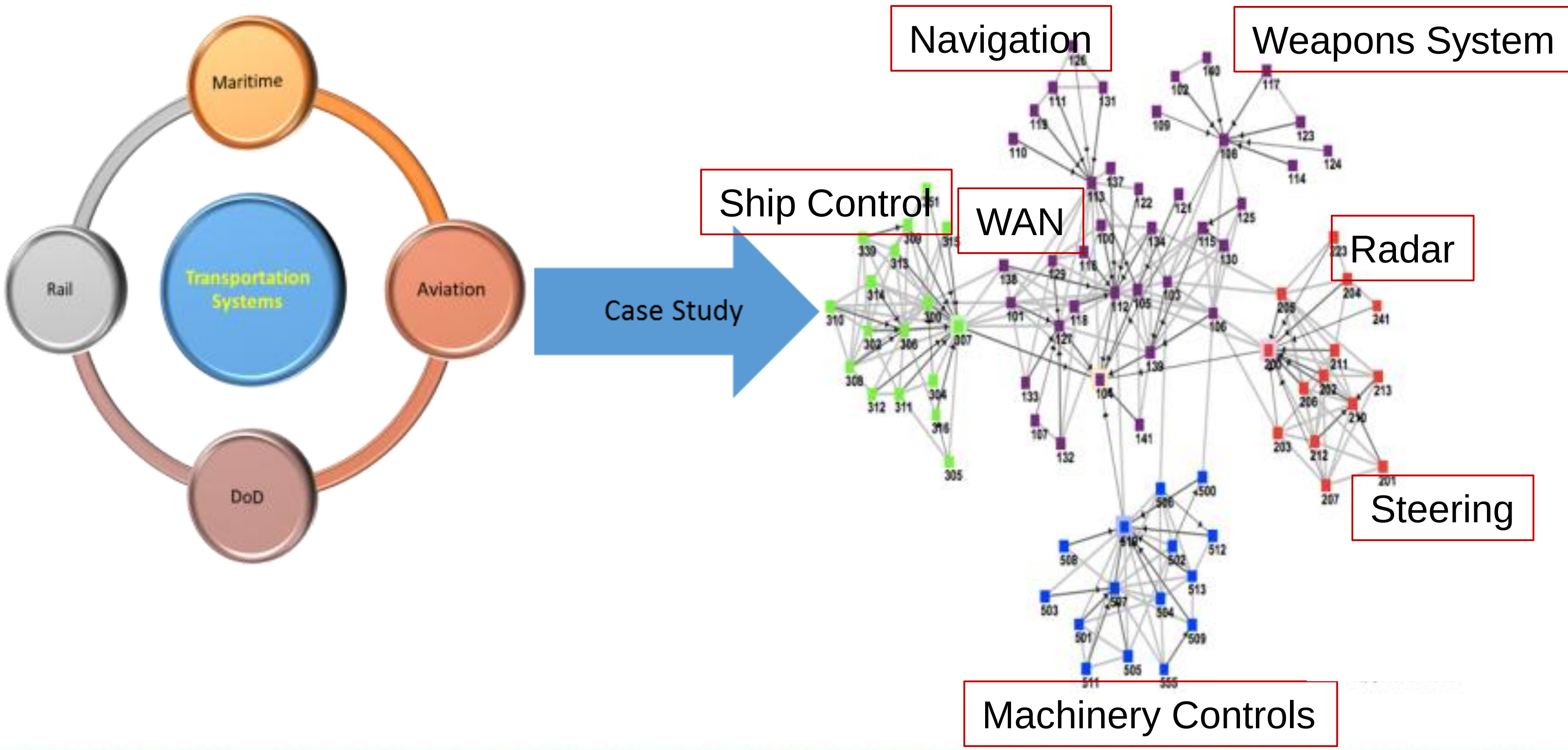
$$f_c = 1 - \frac{1}{\frac{\langle k^2 \rangle}{\langle k \rangle} - 1}$$

Internet percolation transition for networks with power-law connectivity distribution.



What is the common factor?

Complex Network, Interdependence and Resilience



Issues that needs exploring

1. Is real world data useful in building the complex model?
2. Can we quantify relevant properties such as resiliency, reliability, interdependence and find logical relationships?
3. What methods can be used to conceive an appropriate “real system” architecture?

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Biography

Caesar Benipayo has served 27 years in the United States Navy on multiple surface platforms and 10 years experience in shipbuilding industry supporting the LPD 17 Class New Construction Program working in Hull, Mechanical and Electrical systems, Combat and Weapons systems and Program Management. During his Navy tour, Caesar has deployed in Europe, Middle East and Pacific regions onboard AS-31, DD-963, DDG-51, LHD-2, CG-47 and MHC class of ships. His last tour was in NAVSEA as Deputy DDG-51 Class Modernization PM developing the modernization plans for the DDG-51 Class. After retiring from active duty, he was hired as Senior Program Manager to support PMS 317 working on delivering the San Antonio class. He holds a B.S. in Electronics and Communications Engineering from University of Santo Tomas, a Master's in Engineering Management from Old Dominion University and Master in Business Administration from Georgetown University. He is currently a PhD candidate in Systems Engineering at The George Washington University.

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