Assessing the Performance and Vulnerability of Networks from Transportation to the Internet, Financial Networks, and Supply Chains: Which Nodes and Links Really Matter?

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“Understanding and Engineering Systems”
University of Oklahoma, Norman, Oklahoma, April 1, 2013
I would like to thank Dr. Janet K. Allen, John and Mary Moore Chair and Professor of Industrial & Systems Engineering, for inviting me to speak as part of this Dream Course as well as the School of Industrial & Systems Engineering.

I would also like to thank President David L. Boren for the visionary Dream Course initiative at the University of Oklahoma.
Outline

- Background and Motivation
- Characteristics of Networks Today
- Why Behavior Matters and Paradoxes
- Methodologies for Formulation, Analysis, and Computations
- Which Nodes and Links Really Matter?
- Network Performance and Vulnerability
- From Transportation Networks to the Internet
- Financial Networks
- Mergers and Acquisitions and Network Synergies
Background and Motivation
We Are in a New Era of Decision-Making Characterized by:

- *complex interactions* among decision-makers in organizations;
- *alternative and, at times, conflicting criteria* used in decision-making;
- *constraints on resources*: human, financial, natural, time, etc.;
- *global reach* of many decisions;
- *high impact* of many decisions;
- *increasing risk and uncertainty*;
- the *importance of dynamics* and realizing a timely response to evolving events.
Supernetworks are *Networks of Networks*, and their prevalence in the world around us is illustrated by:

- *multimodal transportation networks*;
- *complex supply chain networks consisting of manufacturers, shippers and carriers, distributors, and retailers*;
- *electric power generation and distribution networks*,
- *multitiered financial networks*, and
- *social network platforms such as Facebook and Twitter*, along with the Internet itself.
Multimodal Transportation

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Assessing the Performance and Vulnerability of Networks
Complex Supply Chain Networks

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Assessing the Performance and Vulnerability of Networks
Electric Power Generation and Distribution Networks

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Assessing the Performance and Vulnerability of Networks
Financial Networks

Assessing the Performance and Vulnerability of Networks
Characteristics of Networks Today
Characteristics of Networks Today

- **large-scale nature** and complexity of network topology;
- **congestion**, which leads to nonlinearities;
- **alternative behavior of users of the networks**, which may lead to paradoxical phenomena;
- **possibly conflicting criteria associated with optimization**;
- **interactions among the underlying networks themselves**, such as the Internet with electric power, financial, and transportation and logistical networks;
- recognition of **their fragility and vulnerability**;
- policies surrounding networks today may have major impacts not only economically, but also **socially, politically, and security-wise**.
An Example

In Chicago’s Regional Transportation Network, there are 12,982 nodes, 39,018 links, and 2,297,945 origin/destination (O/D) pairs, whereas in the Southern California Association of Governments model there are 3,217 origins and/or destinations, 25,428 nodes, and 99,240 links, plus 6 distinct classes of users.
In the case of the Internet, in 2012, there were over 2.4 billion users.
Change in Annual Average Congestion Delay Hours for Commuters in the US from 1982 - 2009

Congestion Trends-Yearly Hours of Delay per Auto Commuter

- Washington DC
- Chicago IL-IN
- Baltimore MD
- Philadelphia PA
- Miami FL
- Salt Lake City UT

Congestion costs continue to rise: measured in constant 2011 dollars, the cost of congestion has risen from $24 billion in 1982 to $121 billion in 2011 in the United States. (Texas Transportation Institute’s Urban Mobility Report (2012)).

The average commuter spent an extra 38 hours traveling in 2011, up from 16 hours in 1982. In areas with over 3 million persons, commuters experienced an average of 52 hours of delay in 2011.

In 2011, 2.9 billion gallons of wasted fuel (enough to fill 4 New Orleans Superdomes).

There is a freight capacity crisis in parts of the US.
In a typical user link travel time (or cost) function, the free flow travel time refers to the travel time to traverse the link when there is zero flow or traffic on the link (zero vehicles).
Congestion is Not a New Phenomenon

The study of the efficient operation of transportation networks dates to ancient Rome with a classical example being the publicly provided Roman road network and the time of day chariot policy, whereby chariots were banned from the ancient city of Rome at particular times of day.
Congestion is Not a New Phenomenon

The Oklahoma folks can probably relate more to the land rush of 1889.
Interstate Highway System
Freight Network
World Oil Routes
Natural Gas Flows

Network Systems

Internet Traffic

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Assessing the Performance and Vulnerability of Networks
Interdisciplinary Impact of Networks

Economics and Finance
- Interregional Trade
- General Equilibrium
- Industrial Organization
- Portfolio Optimization
- Flow of Funds
- Accounting

Sociology
- Social Networks
- Organizational Theory

Computer Science
- Routing Algorithms
- Price of Anarchy

OR/MS and Engineering
- Energy
- Manufacturing
- Telecommunications
- Transportation
- Supply Chains

Biology
- DNA Sequencing
- Targeted Cancer Therapy

Models and Algorithms
The components of networks as a theoretical (modeling, analysis, and solution) construct include: nodes, links, and flows.
## Components of Common Physical Networks

<table>
<thead>
<tr>
<th>Network System</th>
<th>Nodes</th>
<th>Links</th>
<th>Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
<td>Intersections, Homes, Workplaces, Airports, Railyards</td>
<td>Roads, Airline Routes, Railroad Track</td>
<td>Automobiles, Trains, and Planes,</td>
</tr>
<tr>
<td>Manufacturing and logistics</td>
<td>Workstations, Distribution Points</td>
<td>Processing, Shipment</td>
<td>Components, Finished Goods</td>
</tr>
<tr>
<td>Communication</td>
<td>Computers, Satellites, Telephone Exchanges</td>
<td>Fiber Optic Cables, Radio Links</td>
<td>Voice, Data, Video</td>
</tr>
<tr>
<td>Energy</td>
<td>Pumping Stations, Plants</td>
<td>Pipelines, Transmission Lines</td>
<td>Water, Gas, Oil, Electricity</td>
</tr>
</tbody>
</table>
It is important to realize that there may be systems that, at first glance, do not seem to be networks, but, after further thought and creativity, one may be able to represent the system as a network!

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- One can then see similarities and differences in structure across different problem domains.
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- One can then see similarities and differences in structure across different problem domains.

- One can avail oneself of powerful network-based analytical tools.
It is important to realize that there may be systems that, at first glance, do not seem to be networks, but, after further thought and creativity, one may be able to represent the system as a network!

The advantages of doing so are many:

• One can then see similarities and differences in structure across different problem domains.

• One can avail oneself of powerful network-based analytical tools.

• One can represent what may be an extremely complex problem graphically through a network, which can suggest further insights and extensions.
Networks consist of nodes, links, flows, and behavior associated with their operation, usage, and management.

Network problems are a distinct class of problems and they come in various forms and formulations, i.e., as optimization (linear or nonlinear) problems or as equilibrium problems and even dynamic network problems.

Methodologies that we have been using and extending to formulate, analyze, and compute solutions to large-scale network problems have included: network optimization, network theory, game theory, multicriteria decision-making, risk management, variational inequality theory, and projected dynamical systems theory.
Why Behavior Matters and Paradoxes
Network Models from Analysis to Design Must Capture the Behavior of Users
Behavior on Congested Networks

*Flows are routed on individual cost-minimizing routes.*

Decentralized vs. Selfish vs. U–O

Centralized vs. Unselfish vs. S–O

System-Optimized

*Flows are routed so as to minimize the total cost.*
Two fundamental principles of flow (traffic) behavior, due to Wardrop (1952), with terms coined by Dafermos and Sparrow (1969).

*User-optimized (U-O) (network equilibrium) Problem* – each user determines his/her cost minimizing route of travel between an origin/destination, until an equilibrium is reached, in which no user can decrease his/her cost of travel by unilateral action (in the sense of Nash).

*System-optimized (S-O) Problem* – users are allocated among the routes so as to minimize the total cost in the system, where the total cost is equal to the sum over all the links of the link’s user cost times its flow.

*The U-O problems, under certain simplifying assumptions, possesses optimization reformulations. But now we can handle cost asymmetries, multiple modes of transport, and different classes of traffic (messages, vehicles, etc.), without such assumptions.*
We Can State These Conditions Mathematically!
The U-O and S-O Conditions

**Definition: U-O or Network Equilibrium – Fixed Demands**
A path flow pattern $x^*$, with nonnegative path flows and O/D pair demand satisfaction, is said to be U-O or in equilibrium, if the following condition holds for each O/D pair $w \in W$ and each path $p \in P_w$:

$$ C_p(x^*) \left\{ \begin{array}{ll}
= \lambda_w, & \text{if } x^*_p > 0, \\
\geq \lambda_w, & \text{if } x^*_p = 0.
\end{array} \right. $$

**Definition: S-O Conditions**
A path flow pattern $x$ with nonnegative path flows and O/D pair demand satisfaction, is said to be S-O, if for each O/D pair $w \in W$ and each path $p \in P_w$:

$$ \hat{C}_p'(x) \left\{ \begin{array}{ll}
= \mu_w, & \text{if } x_p > 0, \\
\geq \mu_w, & \text{if } x_p = 0,
\end{array} \right. $$

where $\hat{C}_p'(x) = \sum_{a \in L} \frac{\partial \hat{c}_a(f_a)}{\partial f_a} \delta_{ap}$, and $\mu_w$ is a Lagrange multiplier.
The Braess Paradox Illustrates Why Behavior on Networks is Important
The Braess (1968) Paradox

Assume a network with a single O/D pair (1,4). There are 2 paths available to travelers: \( p_1 = (a, c) \) and \( p_2 = (b, d) \).

For a travel demand of 6, the equilibrium path flows are \( x_{p_1}^* = x_{p_2}^* = 3 \) and

The equilibrium path travel cost is

\[ C_{p_1} = C_{p_2} = 83. \]
Adding a Link Increases Travel Cost for All!

Adding a new link creates a new path $p_3 = (a, e, d)$.

The original flow distribution pattern is no longer an equilibrium pattern, since at this level of flow the cost on path $p_3$, $C_{p_3} = 70$.

The new equilibrium flow pattern network is $x_{p_1}^* = x_{p_2}^* = x_{p_3}^* = 2$.

The equilibrium path travel cost: $C_{p_1} = C_{p_2} = C_{p_3} = 92$. 

\[ c_e(f_e) = f_e + 10 \]
Under S-O behavior, the total cost in the network is minimized, and the new route $p_3$, under the same demand of 6, would not be used.

The Braess paradox never occurs in S-O networks.
The 1968 Braess article has been translated from German to English and appears as:

“On a Paradox of Traffic Planning,”

The Braess Paradox Around the World

1969 - Stuttgart, Germany - The traffic worsened until a newly built road was closed.

1990 - Earth Day - New York City - 42\textsuperscript{nd} Street was closed and traffic flow improved.

2002 - Seoul, Korea - A 6 lane road built over the Cheonggyecheon River that carried 160,000 cars per day and was perpetually jammed was torn down to improve traffic flow.
Interview on Broadway for *America Revealed* on March 15, 2011
Other Networks that Behave like Traffic Networks

The Internet, electric power networks, supply chains, and even multitiered financial networks!
Methodologies for Formulation, Analysis, and Computations
We utilize the theory of variational inequalities for the formulation, analysis, and solution of both centralized and decentralized network problems.

**Definition: The Variational Inequality Problem**

The finite-dimensional variational inequality problem, $\text{VI}(F, \mathcal{K})$, is to determine a vector $X^* \in \mathcal{K}$, such that:

$$\langle F(X^*)^T, X - X^* \rangle \geq 0, \quad \forall X \in \mathcal{K},$$

where $F$ is a given continuous function from $\mathcal{K}$ to $\mathbb{R}^N$, $\mathcal{K}$ is a given closed convex set, and $\langle \cdot, \cdot \rangle$ denotes the inner product in $\mathbb{R}^N$. 

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The variational inequality problem contains, as special cases, such mathematical programming problems as:

- systems of equations,
- optimization problems,
- complementarity problems,
- and is related to the fixed point problem.

_Hence, it is a natural methodology for a spectrum of congested network problems from centralized to decentralized ones as well as to design problems._
In particular, $F(X^*)$ is “orthogonal” to the feasible set $\mathcal{K}$ at the point $X^*$.

Associated with a VI is a Projected Dynamical System, which provides a natural underlying dynamics associated with travel (and other) behavior to the equilibrium.
To model the *dynamic behavior of supernetworks*, including transportation networks and supply chains, we utilize *projected dynamical systems* (PDSs) advanced by Dupuis and Nagurney (1993) in *Annals of Operations Research* and by Nagurney and Zhang (1996) in our book *Projected Dynamical Systems and Variational Inequalities with Applications*.

Such nonclassical dynamical systems are now being used in

*evolutionary games* (Sandholm (2005, 2011)),

*ecological predator-prey networks* (Nagurney and Nagurney (2011a, b)), and

even *neuroscience* (Girard et al. (2008)).
Some of My Books

- Network Economics: A Variational Inequality Approach, Revised Second Edition
- FRAGILE NETWORKS: Identifying Vulnerabilities and Synergies in an Uncertain World
- Financial Networks: Stability and Dynamics
- Supply Chain Network Economics: Dynamics of Prices, Flows and Profits
- Projected Dynamical Systems and Variational Inequalities with Applications
- Innovations in Financial and Economic Networks
- Supernetworks: Decision-Making for the Information Age
Recall the Braess network with the added link e.

What happens as the demand increases?
For Networks with Time-Dependent Demands
We Use Evolutionary Variational Inequalities
Research with Professor David Parkes of Harvard University and Professor Patrizia Daniele of the University of Catania, Italy
The U-O Solution of the Braess Network with Added Link (Path) and Time-Varying Demands Solved as an Evolutionary Variational Inequality in a Model of the Internet (Nagurney, Daniele, and Parkes (2007)).
In Demand Regime I, Only the New Path is Used.
In Demand Regime II, the demand lies in the range [2.58, 8.89], and the Addition of a New Link (Path) Makes Everyone Worse Off!
In Demand Regime III, when the demand exceeds 8.89, Only the Original Paths are Used!

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The new path is never used, under U-O behavior, when the demand exceeds 8.89, even out to infinity!
Which Nodes and Links Really Matter?
The analysis and the identification of the vulnerable components in networks have, recently, emerged as a major research theme.

However, in order to be able to evaluate the vulnerability and the reliability of a network, a measure that can quantifiably capture the performance of a network must be developed.
Recent disasters have vividly demonstrated the importance and vulnerability of our critical infrastructure systems:

- The biggest blackout in North America, August 14, 2003;
- Two significant power outages in September 2003 – one in the UK and the other in Italy and Switzerland;
- The Indonesian tsunami (and earthquake), December 26, 2004;
- Hurricane Katrina, August 23, 2005;
- The Minneapolis I35 Bridge collapse, August 1, 2007;
- The Mediterranean cable destruction, January 30, 2008;
- The Sichuan earthquake on May 12, 2008;
- The Haiti earthquake that struck on January 12, 2010 and the Chilean one on February 27, 2010;
- The triple disaster in Japan on March 11, 2011.
Hurricane Katrina in 2005

Hurricane Katrina has been called an "American tragedy," in which essential services failed completely.
The Haitian and Chilean Earthquakes
The Triple Disaster in Japan on March 11, 2011

Now the world is reeling from the aftereffects of the triple disaster in Japan with disruptions in the high tech, automotive, and even food industries with potential additional ramifications because of the radiation.
Disasters Also Happen Closer to Home

Bridge Creek – Oklahoma City – Moore – Del City tornado on May 3, 1999 with losses at $1 billion
Disasters have brought an unprecedented impact on human lives in the 21st century and the number of disasters is growing. From January to October 2005, an estimated 97,490 people were killed in disasters globally; 88,117 of them because of natural disasters.

Frequency of disasters [Source: Emergency Events Database (2008)]
Natural Disasters (1975–2008)

- Number of natural disasters reported:
  - Peak around 2005
  - Increasing trend from 1975 to 2008

- Number of people reported affected by natural disasters:
  - Spike in 2005
  - Generally increasing trend from 1975 to 2008
Disasters have a catastrophic effect on human lives and a region’s or even a nation’s resources and economies.

By being able to identify which are the most important nodes and links we can then invest appropriately to protect such network components.
The network performance/efficiency measure, $\mathcal{E}(G, d)$, for a given network topology $G$ and the equilibrium (or fixed) demand vector $d$, is:

$$\mathcal{E} = \mathcal{E}(G, d) = \frac{\sum_{w \in W} d_w}{\lambda_w n_W},$$

where recall that $n_W$ is the number of O/D pairs in the network, and $d_w$ and $\lambda_w$ denote, for simplicity, the equilibrium (or fixed) demand and the equilibrium disutility for O/D pair $w$, respectively.
**Definition: Importance of a Network Component**

The importance of a network component $g \in G$, $I(g)$, is measured by the relative network efficiency drop after $g$ is removed from the network:

$$I(g) = \frac{\Delta \mathcal{E}}{\mathcal{E}} = \frac{\mathcal{E}(G, d) - \mathcal{E}(G - g, d)}{\mathcal{E}(G, d)}$$

where $G - g$ is the resulting network after component $g$ is removed from network $G$. 

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The elimination of a link is treated in the N-Q network efficiency measure by removing that link while the removal of a node is managed by removing the links entering and exiting that node.

In the case that the removal results in no path connecting an O/D pair, we simply assign the demand for that O/D pair to an abstract path with a cost of infinity.

The N-Q measure is well-defined even in the case of disconnected networks.
The Advantages of the N-Q Network Efficiency Measure

- The measure captures \textit{demands, flows, costs, and behavior of users}, in addition to \textit{network topology}.

- The resulting importance definition of network components is applicable and \textit{well-defined} even in the case of \textit{disconnected networks}.

- It can be used to identify the \textit{importance (and ranking) of either nodes, or links, or both}.

- It can be applied to \textit{assess the efficiency/performance of a wide range of network systems, including financial systems and supply chains under risk and uncertainty}.

- It is applicable also to \textit{elastic demand networks}.

- It is \textit{applicable to dynamic networks, including the Internet}.
Some Applications of the N-Q Measure
Figure 1: The Sioux Falls network with 24 nodes, 76 links, and 528 O/D pairs of nodes.
Importance of Links in the Sioux Falls Network

The computed network efficiency measure $E$ for the Sioux Falls network is $E = 47.6092$. Links 27, 26, 1, and 2 are the most important links, and hence special attention should be paid to protect these links accordingly, while the removal of links 13, 14, 15, and 17 would cause the least efficiency loss.

Figure 2: The Sioux Falls network link importance rankings
According to the European Environment Agency (2004), since 1990, the annual number of extreme weather and climate related events has doubled, in comparison to the previous decade. These events account for approximately 80% of all economic losses caused by catastrophic events. In the course of climate change, catastrophic events are projected to occur more frequently (see Schulz (2007)).

Schulz (2007) applied *N-Q network efficiency measure* to a German highway system in order to identify the critical road elements and found that this measure provided more reasonable results than the measure of Taylor and DEste (2007).

The N-Q measure can also be used to assess which links should be added to improve efficiency. *This measure was used for the evaluation of the proposed North Dublin (Ireland) Metro system* (October 2009 Issue of *ERCIM News*).
Figure 3: Comparative Importance of the links for the Baden-Württemberg Network – Modelling and analysis of transportation networks in earthquake prone areas via the N-Q measure, Tyagunov et al.
From Transportation Networks to the Internet
The network efficiency for the network $G$ with time-varying demand $d$ for $t \in [0, T]$, denoted by $\mathcal{E}(G, d, T)$, is defined as follows:

$$
\mathcal{E}(G, d, T) = \frac{\int_0^T \left[ \sum_{w \in W} \frac{d_w(t)}{\lambda_w(t)} \right] / n_W \, dt}{T}.
$$

Note that the above measure is the average network performance over time of the dynamic network.
Let $d_{w1}^1, d_{w2}^2, ..., d_{wH}^H$ denote demands for O/D pair $w$ in $H$ discrete time intervals, given, respectively, by: $[t_0, t_1], (t_1, t_2], ..., (t_{H-1}, t_H]$, where $t_H \equiv T$. We assume that the demand is constant in each such time interval for each O/D pair. Moreover, we denote the corresponding minimal costs for each O/D pair $w$ at the $H$ different time intervals by: $\lambda_{w1}^1, \lambda_{w2}^2, ..., \lambda_{wH}^H$. The demand vector $d$, in this special discrete case, is a vector in $\mathbb{R}^{n_{W \times H}}$.

**Dynamic Network Efficiency: Discrete Time Version**

The network efficiency for the network $(G, d)$ over $H$ discrete time intervals:

$[t_0, t_1], (t_1, t_2], ..., (t_{H-1}, t_H]$, where $t_H \equiv T$, and with the respective constant demands:

$d_{w1}^1, d_{w2}^2, ..., d_{wH}^H$ for all $w \in W$ is defined as follows:

\[
\mathcal{E}(G, d, t_H = T) = \frac{\sum_{i=1}^H \left[ (\sum_{w \in W} \frac{d_{w}^i}{\lambda_{w}^i})(t_i - t_{i-1})/n_W \right]}{t_H}.
\]
Assume that $d_w(t) = d_w$, for all O/D pairs $w \in W$ and for $t \in [0, T]$. Then, the dynamic network efficiency measure collapses to the Nagurney and Qiang measure:

$$E = \frac{1}{n_W} \sum_{w \in W} \frac{d_w}{\lambda_w}.$$
The importance of network component $g$ of network $G$ with demand $d$ over time horizon $T$ is defined as follows:

$$I(g, d, T) = \frac{\mathcal{E}(G, d, T) - \mathcal{E}(G - g, d, T)}{\mathcal{E}(G, d, T)}$$

where $\mathcal{E}(G - g, d, T)$ is the dynamic network efficiency after component $g$ is removed.
The U-O Solution of the Braess Network with Added Link (Path) and Time-Varying Demands Solved as an *Evolutionary Variational Inequality* in a Model of the Internet (Nagurney, Daniele, and Parkes (2007)).

![Graph](image)

**Legend:**
- **Paths 1 and 2**
- **Path 3**
Importance of Nodes and Links in the Dynamic Braess Network Using the New Measure When $T = 10$

<table>
<thead>
<tr>
<th>Link</th>
<th>Importance Value</th>
<th>Importance Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>0.2604</td>
<td>1</td>
</tr>
<tr>
<td>$b$</td>
<td>0.1784</td>
<td>2</td>
</tr>
<tr>
<td>$c$</td>
<td>0.1784</td>
<td>2</td>
</tr>
<tr>
<td>$d$</td>
<td>0.2604</td>
<td>1</td>
</tr>
<tr>
<td>$e$</td>
<td>-0.1341</td>
<td>3</td>
</tr>
</tbody>
</table>

Link $e$ is never used after $t = 8.89$ and in the range $t \in [2.58, 8.89]$, it increases the cost, so the fact that link $e$ has a negative importance value makes sense; over time, its removal would, on the average, improve the network efficiency!

<table>
<thead>
<tr>
<th>Node</th>
<th>Importance Value</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0000</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.2604</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0.2604</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1.0000</td>
<td>1</td>
</tr>
</tbody>
</table>
Envisioning a New Kind of Internet

We are one of five teams funded by NSF as part of the Future Internet Architecture (FIA) project.

Our project is: Network Innovation Through Choice and the envisioned architecture is ChoiceNet.

Team:

University of Kentucky: Jim Griffioen, Ken Calvert
North Carolina State University: Rudra Dutta, George Rouskas
RENCI/UNC: Ilia Baldine
University of Massachusetts Amherst: Tilman Wolf, Anna Nagurney
**ChoiceNet Principles**

*Competition Drives Innovation!*

**Services are at core of ChoiceNet**
(“everything is a service”)

Services provide a benefit, have a cost

Services are created, composed, sold, verified, etc.

*Encourage alternatives*  Provide building blocks for different types of services

*Know what happened*  Ability to evaluate services

*Vote with your wallet*  Reward good services!
ChoiceNet Architecture

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Assessing the Performance and Vulnerability of Networks
Financial Networks
The study of financial networks dates to the 1750s when Quesnay (1758), in his *Tableau Economique*, conceptualized the circular flow of financial funds in an economy as a network.
The advances in information technology and globalization have further shaped today’s financial world into a complex network, which is characterized by distinct sectors, the proliferation of new financial instruments, and with increasing international diversification of portfolios.
As pointed out by Sheffi (2005) in his book, *The Resilient Enterprise*, one of the main characteristics of disruptions in networks is “the seemingly unrelated consequences and vulnerabilities stemming from global connectivity.”
In 2008 and 2009, the world reeled from the effects of the financial credit crisis; leading financial services and banks closed (including the investment bank Lehman Brothers), others merged, and the financial landscape was changed for forever.
In 2008 and 2009, the world reeled from the effects of the financial credit crisis; leading financial services and banks closed (including the investment bank Lehman Brothers), others merged, and the financial landscape was changed for forever.

The domino effect of the U.S. economic troubles rippled through overseas markets and pushed countries such as Iceland to the verge of bankruptcy.
Financial Networks

It is crucial for the decision-makers in financial systems (managers, executives, and regulators) to be able to identify a financial network's vulnerable components to protect the functionality of the network.

Financial networks, as extremely important infrastructure networks, have a great impact on the global economy, and their study has recently also attracted attention from researchers in the area of complex networks.

Recent empirical research has shown that connections increase before and during financial crises.

Granger Causality Results: Green Broker, Red Hedge Fund, Black Insurer, Blue Bank  
Source: Billio, Getmansky, Lo, and Pelizzon (2011)

Nevertheless, there is very little literature that addresses the vulnerability of financial networks.

Our network performance measure for financial networks captures both economic behavior as well as the underlying network/graph structure and the dynamic reallocation after disruptions.
Assessing the Performance and Vulnerability of Networks
The Financial Network Model with Intermediation

Sources of Financial Funds

Internet Links

Intermediaries

Demand Markets - Uses of Funds
Examples of source agents include households and businesses.

The financial intermediaries, in turn, which can include banks, insurance companies, investment companies, etc., in addition to transacting with the source agents determine how to allocate the incoming financial resources among the distinct uses or financial products associated with the demand markets, which correspond to the nodes at the bottom tier of the financial network in the figure.

Both source agents and intermediaries maximize their net revenues while minimizing their risk.

Examples of demand markets are: the markets for real estate loans, household loans, business loans, etc.
Definition: The Financial Network Performance Measure

The financial network performance measure, \( \mathcal{E}^F \), for a given network topology \( G \), and demand price functions \( \rho_{3k}(d) \) \((k = 1, 2, \ldots, o)\), and available funds held by source agents \( S \), is defined as follows:

\[
\mathcal{E}^F = \sum_{k=1}^{o} \frac{d_k^*}{\rho_{3k}(d^*)},
\]

where \( o \) is the number of demand markets in the financial network, and \( d_k^* \) and \( \rho_{3k}(d^*) \) denote the equilibrium demand and the equilibrium price for demand market \( k \), respectively.
The financial network performance is expected to deteriorate when a critical network component is eliminated from the network.

Such a component can include a link or a node or a subset of nodes and links depending on the financial network problem under investigation. Furthermore, the removal of a critical network component will cause severe damage than that of the damage caused by a trivial component.
The importance of a network component is defined as:

**Definition: Importance of a Financial Network Component**

The importance of a financial network component \( g \in G \), \( I(g) \), is measured by the relative financial network performance drop after \( g \) is removed from the network:

\[
I(g) = \frac{\Delta \mathcal{E}^F}{\mathcal{E}^F} = \frac{\mathcal{E}^F(G) - \mathcal{E}^F(G - g)}{\mathcal{E}^F(G)}
\]

where \( G - g \) is the resulting financial network after component \( g \) is removed from network \( G \).
According to a recent survey conducted by PriceWaterhouseCoopers (2012), with over 3,800 respondents in 78 countries, cybercrime is placing heavy strains on the global financial sector, with cybercrime now the second most commonly reported economic crime affecting financial services firms. Cybercrime accounted for 38% of all economic crimes in the financial sector, as compared to an average of 16% across all other industries. The Ponemon Institute (2011) reports that the median annualized cost of cybercrimes to 50 organizations in its study was $5.9 million a year, with a range of $1.5 million to $36.5 million per company. Cyber attacks are intrusive and economically costly. In addition, they may adversely affect a company's most valuable asset - its reputation.
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Cybercrime and Financial Institutions

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Green Nodes represent Institutions.
Red Nodes represent the Attackers.
Red Edges between Attackers can represent collusion or transactions of stolen goods.
Black Edges between Institutions can show sharing of information and mutual dependence.
Blue Edges between the Attacker and Institution can represent threats and attacks.
Mergers and Acquisitions and Network Synergies
A successful merger depends on the ability to measure the anticipated synergy of the proposed merger (cf. Chang (1988)).

The rest of this presentation is based on the recent paper:

It is increasingly apparent and documented that improving supply chain integration is key to improving the likelihood of post-merger success!

This is understandable, since up to 80% of a firm’s costs are linked to operations (Benitez and Gordon (2000)).

However, empirical studies demonstrate that one out of two post-merger integration efforts fares poorly (Gerds and Schewe (2009)).
In addition, in an empirical analysis of a global sample of over 45,000 data points of post-merger transactions in all significant sectors globally from services to manufacturing, risk factors were identified to post-merger success (see Gerds, Strottmann, and Jayaprakash (2010)).
Risk in the context of supply chains may be associated with
• the production/procurement processes,
• the transportation/shipment of the goods,
• and/or the demand markets.

Such supply chain risks are directly reflected in firms’ financial performances, and priced in the financial market.

Hendricks and Singhal (2010) estimated that the average stock price reaction to supply-demand mismatch announcements was approximately $-6.8\%$. In addition, supply chain disruptions can cause firms’ equity risks to increase by $13.50\%$ on average after the disruption announcements (Hendricks and Singhal (2005)).
Illustrations of Supply Chain Risk
We build upon the recent work in mergers and acquisitions of that focuses on horizontal network integration (cf. Nagurney (2009), Nagurney and Woolley (2010), and Nagurney, Woolley, and Qiang (2010)).

We have developed the following significant extension: we utilize a mean-variance (MV) approach in order to capture the risk associated with supply chain activities both prior to and post the merger/acquisition under investigation. The MV approach to the measurement of risk dates to the work of the Nobel laureate Markowitz (1952, 1959) and even today (cf. Schneeweis, Crowder, and Kazemi (2010)) remains a fundamental approach to minimizing volatility.
The Pre- and Post-Merger Supply Chain Networks
All firms, both prior and post the merger, minimize both their expected total costs and the risk, as captured through the variance of the total costs, with a suitable weight assigned to the latter.
Figure 5: The Pre-Merger Supply Chain Network
Figure 6: The Post-Merger Supply Chain Network