

# Networks to Save the World: Operations Research in Action

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# Acknowledgments

Es un gran honor y me da una gran satisfacción encontrarme hoy aquí, con ustedes.



Muchas gracias por todo.

# Outline

- ▶ Background and Inspiration
- ▶ Network Systems and the Braess Paradox
- ▶ Representation of Supply Chains as Networks
- ▶ Supply Chain Networks from Healthcare to Food
- ▶ Network Models and Disaster Relief
- ▶ Cybercrime and Cybersecurity
- ▶ Envisioning a New Kind of Internet - ChoiceNet

# Background and Inspiration



# Work in the Naval Defense Sector

After receiving my undergraduate degrees from Brown University in Applied Mathematics and in Russian Language and Literature, I worked in the naval defense sector in beautiful Newport, Rhode Island. My work for two different companies focused on software development for submarines, and, later, on mathematical modeling using networks and optimization. Newport is also the location of the Naval War College.



# First Conference Presentation and Publication

My research work at NUSC, now NUWC (Naval Undersea Warfare Center), was presented at a conference at the Naval Postgraduate School in Monterey, California. The title of my paper was, "The Role of Optimal Routing in Multiplatform Naval Task Force Operations," published in the *Proceedings of the Second MIT/ONR Workshop on Distributed Communication and Decision Problems Motivated by Naval C<sup>3</sup> Systems*.



**I was the only female speaker at this conference.**

# Off to Grad School for a PhD

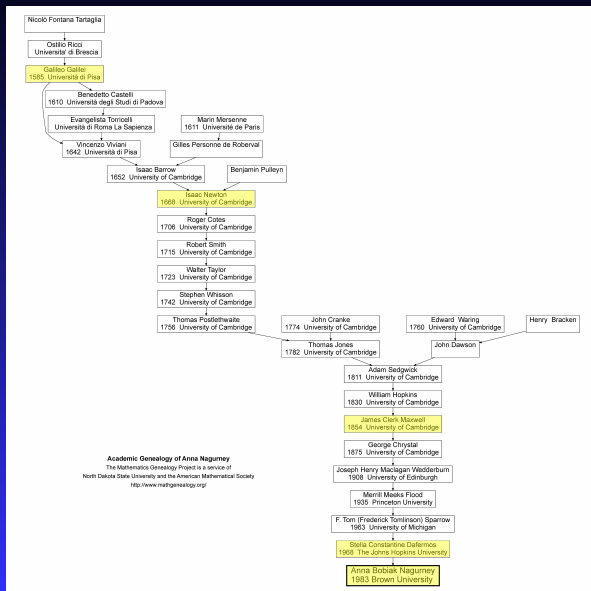
**Very soon I realized that I wanted a PhD because of the research!**

Dr. Stella Dafermos was the only female professor at the time in either Engineering or Applied Mathematics at Brown University. I became her first PhD student.



**Stella was the second female to receive a PhD in Operations Research (OR) and that was from Johns Hopkins University.**

# On the Shoulders of Giants - Academic Genealogy



# Connections to the US Navy Continue

I had a job offer to be a professor at the US Naval Academy in Annapolis, Maryland but joined the faculty at the University of Massachusetts Amherst.

The connections to the US Navy continue with my brother and niece working in the defense sector and with my niece on the USS Zumwalt, being based in San Diego now.



# Networks in Transportation and Logistics

**Networks have assisted in transportation and logistics in numerous sectors, including defense.**

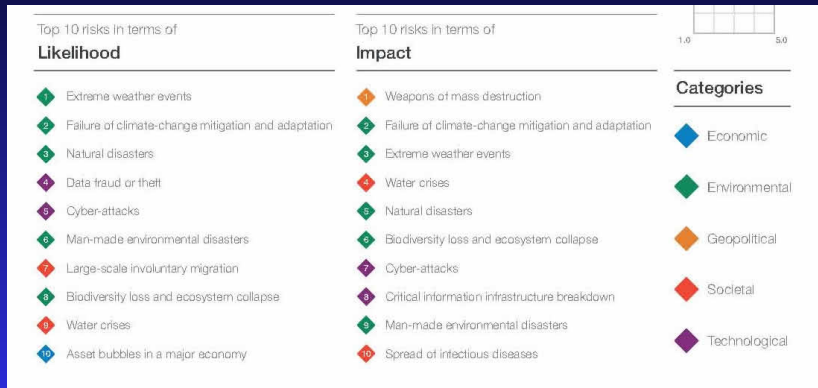
The science of networks dates to **1736 - Euler** - the earliest paper on graph theory - Königsberg bridges problem. **1781 - Monge**, who had worked under Napoleon Bonaparte, publishes what is probably the first paper on transportation in minimizing cost.

And, one of my favorite sayings that I share with my students in my Humanitarian Logistics class is:

**“There is an old military saying, which speaks volumes: Armchair generals talk strategy. Real generals talk logistics.”**

# Some of the Biggest Global Challenges

**The World Economic Forum identified 10 biggest global challenges, including:**



# Network Systems and the Braess Paradox



# I Work on the Modeling of Network Systems



And utilize optimization, game theory, and also dynamical systems to gain insights as to the behavior of stakeholders.

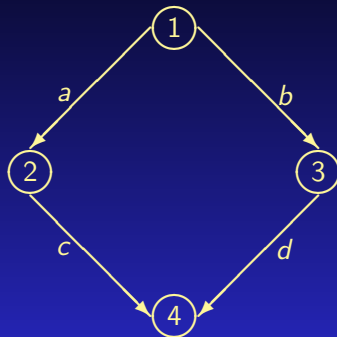
# Importance of Capturing Behavior on Networks - The Braess (1968) Paradox and User-Optimizing (U-O) Behavior

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

$$C_{p_1} = C_{p_2} = 83.$$



$$c_a(f_a) = 10f_a, \quad c_b(f_b) = f_b + 50,$$

$$c_c(f_c) = f_c + 50, \quad c_d(f_d) = 10f_d.$$

# Adding a Link Increases Travel Cost for All!

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

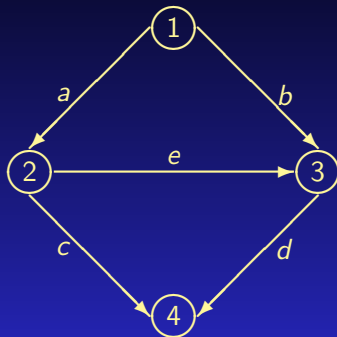
The original flow distribution pattern is no longer an equilibrium pattern, since at this level of flow the cost on path  $p_3$ ,  $C_{p_3} = 70$ .

The new equilibrium flow pattern network is

$$x_{p_1}^* = x_{p_2}^* = x_{p_3}^* = 2.$$

The equilibrium path travel cost:

$$C_{p_1} = C_{p_2} = C_{p_3} = 92.$$



$$c_e(f_e) = f_e + 10$$



# 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<sup>nd</sup> 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.





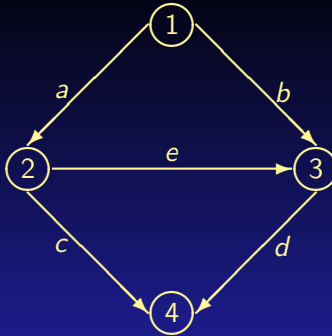
# Interview on Broadway for *America Revealed* on March 15, 2011



Under System-optimizing (S-O) behavior, the total cost in the network is minimized, and the new route  $p_3$ , under the same demand, would not be used.

*The Braess paradox never occurs in S-O networks and can occur only in User-Optimized (U-O) networks.*

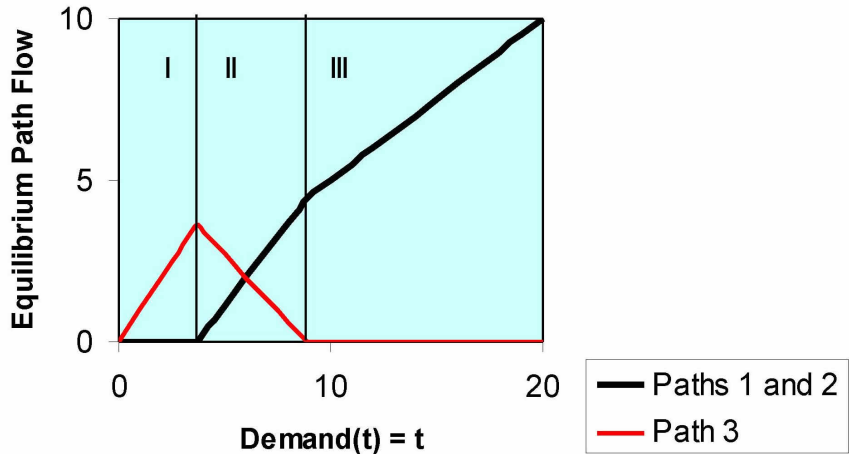




Recall the Braess network with the added link  $e$ .

*What happens as the demand increases?*

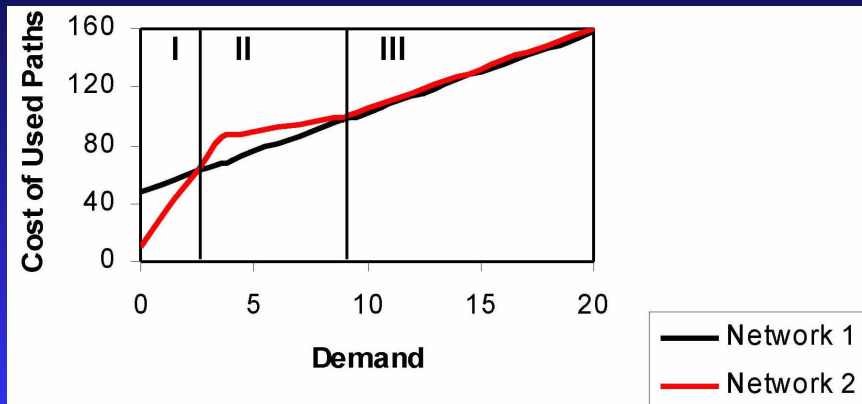
The U-O Solution of the Braess Network with Added Link (Path) and Time-Varying Demands Solved as an *Evolutionary Variational Inequality* (A. Nagurney, P. Daniele, and D. Parkes, *Computational Management Science* **4** (2007), pp 355-375).



In Demand Regime I, **Only the New Path is Used.**

In Demand Regime II, the travel demand lies in the range [2.58, 8.89], and *the Addition of a New Link (Path) Makes Everyone Worse Off!*

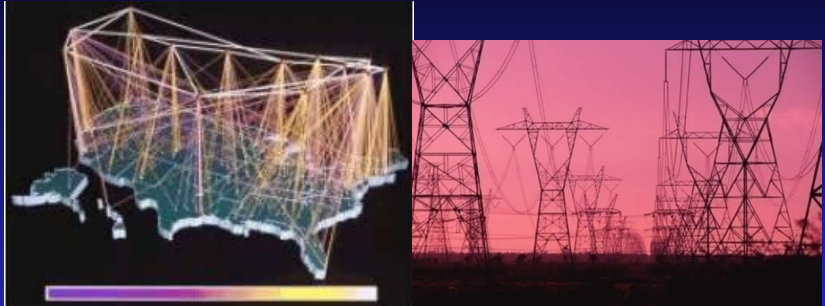
In Demand Regime III, when the travel demand exceeds 8.89, **Only the Original Paths are Used!**



*The new path is never used, under U-O behavior, when the demand exceeds 8.89, even when the demand goes out to infinity!*



# Other Networks that Behave like Traffic Networks



The Internet and electric power networks and even supply chains!

# Representation of Supply Chains as Networks

# Much of My Recent Research Has Been on Supply Chains



# Characteristics of Supply Chains and 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 networks, financial networks, 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*.



# Methodology - The Variational Inequality Problem

We utilize the theory of variational inequalities for the formulation, analysis, and solution of numerous network problems.

## **Definition: The Variational Inequality Problem**

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

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

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

# Methodology - The Variational Inequality Problem

The vector  $X$  consists of the decision variables – typically, the flows (products, prices, investments, security levels, etc.).

$\mathcal{K}$  is the feasible set representing how the decision variables are constrained – for example, the flows may have to be nonnegative; budget constraints may have to be satisfied; similarly, quality and/or time constraints may have to be satisfied.

The function  $F$  that enters the variational inequality represents functions that capture the behavior in the form of the functions such as costs, profits, risk, etc.

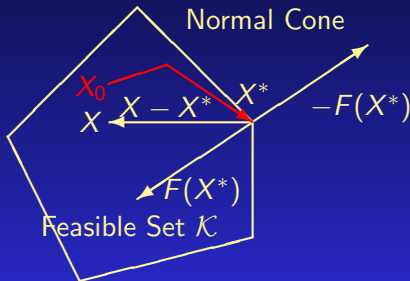
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- systems of equations,
- optimization problems,
- complementarity problems,
- game theory problems, operating under Nash equilibrium,
- and is related to the fixed point problem.

*Hence, it is a natural methodology for a spectrum of supply chain network problems from centralized to decentralized ones as well as to design problems.*

# Geometric Interpretation of $\text{VI}(F, \mathcal{K})$ and a Projected Dynamical System (Dupuis and Nagurney, Nagurney and Zhang)

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 natural underlying dynamics associated with travel (and other) behavior to the equilibrium.

To model the *dynamic behavior of complex networks*, 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) *dynamic spectrum model for cognitive radio networks* (Setoodeh, Haykin, and Moghadam (2012)).

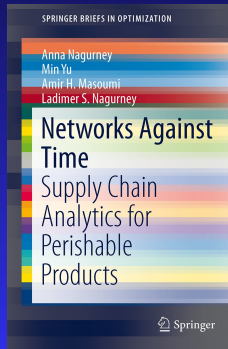
# Some of My Books



# Supply Chain Networks from Healthcare to Food

# A Multidisciplinary Approach

In our research on perishable and time-sensitive product supply chains, we utilize results from physics, chemistry, biology, and medicine in order to capture the perishability of various products over time from healthcare products such as blood, medical nucleotides, and pharmaceuticals to food.





# Supply Chain Networks – Optimization Models

# Blood Supply Chains for the Red Cross

A. Nagurney, A.H. Masoumi, and M. Yu, "Supply Chain Network Operations Management of a Blood Banking System with Cost and Risk Minimization," *Computational Management Science* **9(2)** (2012), pp 205-231.



# Blood Supply Chains for the Red Cross

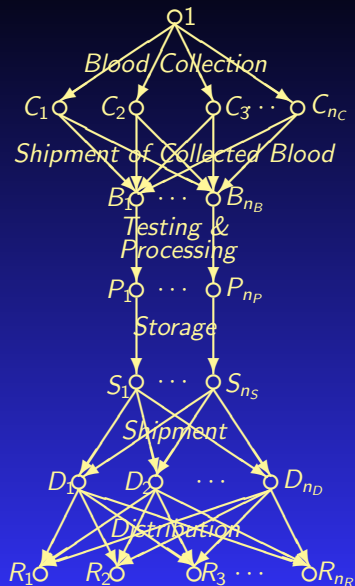
The American Red Cross is the major supplier of blood products to hospitals and medical centers satisfying about **40%** of the demand for blood components nationally.



# Blood Supply Chains for the Red Cross

- ▶ The shelf life of platelets is 5 days and of red blood cells is 42.
- ▶ Over 39,000 donations are needed everyday in the US.
- ▶ Blood is a perishable product that cannot be manufactured but must be donated.
- ▶ As of February 1, 2018, the American Red Cross was facing a critical emergency need for blood and platelet donors. Severe winter weather forced the cancellation of hundreds of blood drives, resulting in nearly tens of thousands donations uncollected. In addition, flu in the US was close to epidemic levels.
- ▶ There is increasing competition among blood service organizations for donors and, overall, there has been a decrease in demand because of improved medical procedures.

# Supply Chain Network Topology for a Regionalized Blood Bank



ARC Regional Division

Blood Collection Sites

Blood Centers

Component Labs

Storage Facilities

Distribution Centers

Demand Points

# Blood Supply Chains for the Red Cross

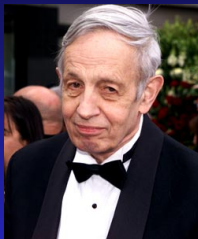
Our blood supply chain network optimization model for the management of the procurement, testing and processing, and distribution has such novel features as:

- ▶ It captures *perishability of this life-saving product* through the use of arc multipliers;
- ▶ It contains *discarding costs* associated with waste/disposal;
- ▶ It handles *uncertainty* associated with demand points;
- ▶ It assesses *costs associated with shortages/surpluses at the demand points*, and
- ▶ It quantifies the *supply-side risk* associated with procurement.

# Supply Chain Networks – Game Theory Models

# Game Theory

There are many game theory problems and tools for solving them. There is noncooperative game theory, in which the players or decision-makers compete with one another, and cooperative game theory, in which players cooperate with one another.



John F. Nash

In **noncooperative games**, the governing concept is that of Nash equilibrium. In **cooperative games**, we can apply Nash bargaining theory.



# Electric Power Supply Chains

We developed *an empirical, large-scale electric supply chain network equilibrium model*, formulated it as a VI problem, and were able to solve it by *exploiting the connection between electric power supply chain networks and transportation networks* using our proof of a hypothesis posed in the classic book, *Studies in the Economics of Transportation*, by Beckmann, McGuire, and Winsten (1956).

The paper, “An Integrated Electric Power Supply Chain and Fuel Market Network Framework: Theoretical Modeling with Empirical Analysis for New England,” by Z. Liu and A. Nagurney, was published in *Naval Research Logistics* **56** (2009), pp 600-624.

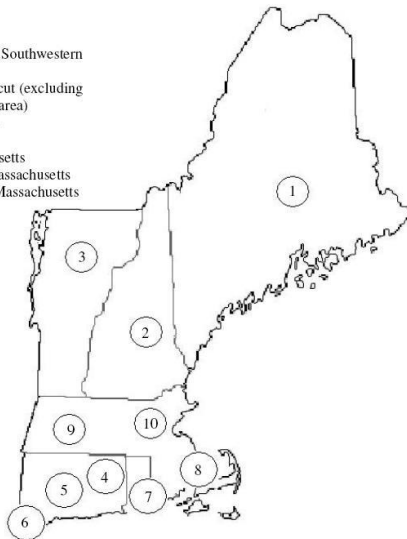
# An Empirical Example of an Electric Power Supply Chain for New England

There are 82 generating companies who own and operate 573 generating units. We considered 5 types of fuels: natural gas, residual fuel oil, distillate fuel oil, jet fuel, and coal. The whole area was divided into 10 regions:

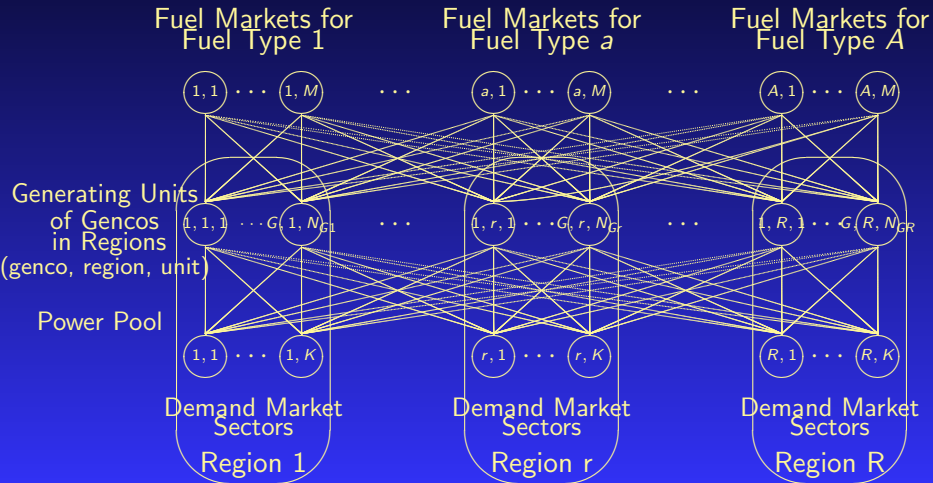
1. Maine,
2. New Hampshire,
3. Vermont,
4. Connecticut (excluding Southwest Connecticut),
5. Southwestern Connecticut (excluding the Norwalk-Stamford area),
6. Norwalk-Stamford area,
7. Rhode Island,
8. Southeastern Massachusetts,
9. Western and Central Massachusetts,
10. Boston/Northeast Massachusetts.

# Graphic of New England

1. Maine
2. New Hampshire
3. Vermont
4. Connecticut (excluding Southwestern Connecticut)
5. Southwestern Connecticut (excluding the Norwalk-Stamford area)
6. Norwalk-Stamford area
7. Rhode Island
8. Southeastern Massachusetts
9. Western and Central Massachusetts
10. Boston/Northeastern Massachusetts



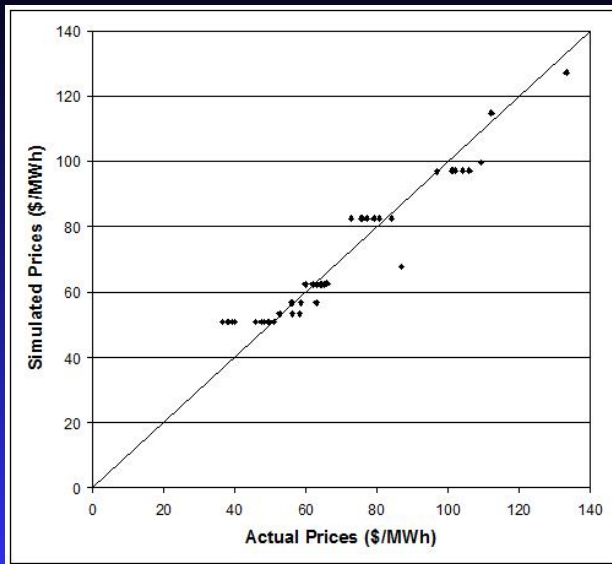
# The Electric Power Supply Chain Network with Fuel Supply Markets



We tested the model on the data of July 2006 which included  $24 \times 31 = 744$  hourly demand/price scenarios. We sorted the scenarios based on the total hourly demand, and constructed the load duration curve. We divided the duration curve into 6 blocks ( $L_1 = 94$  hours, and  $L_w = 130$  hours;  $w = 2, \dots, 6$ ) and calculated the average regional demands and the average weighted regional prices for each block.

*The empirical model had on the order of 20,000 variables.*

# Actual Prices Vs. Simulated Prices (\$/Mwh)



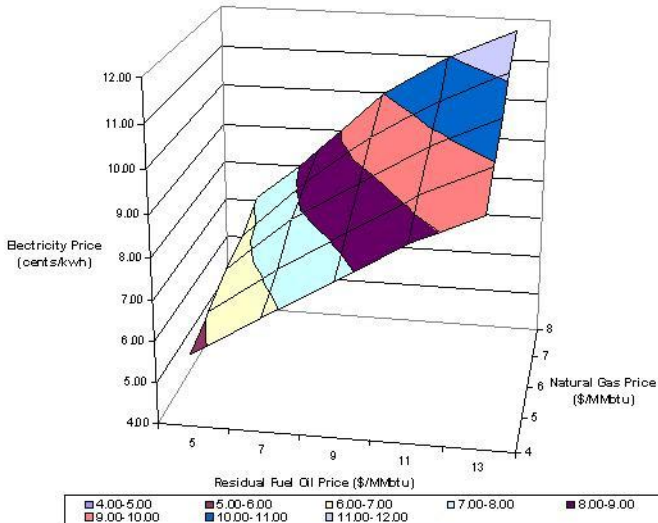
# Sensitivity Analysis

We used the same demand data, and then varied the prices of natural gas and residual fuel oil. We assumed that the percentage change of distillate fuel oil and jet fuel prices were the same as that of the residual fuel oil price.

The next figure presents the average electricity price for the two peak blocks under oil/gas price variations.

The surface in the figure represents the average peak electricity prices under different natural gas and oil price combinations.

# Sensitivity Analysis













# Food Supply Chains

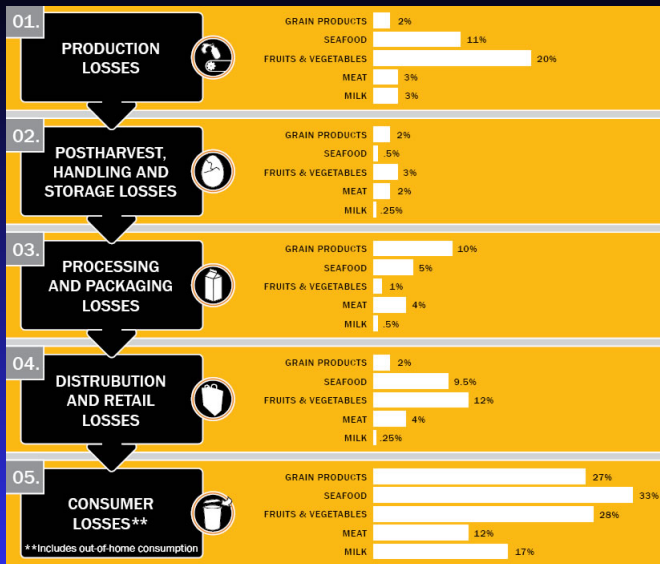
Food is something anyone can relate to.



# Fascinating Facts About Food Perishability

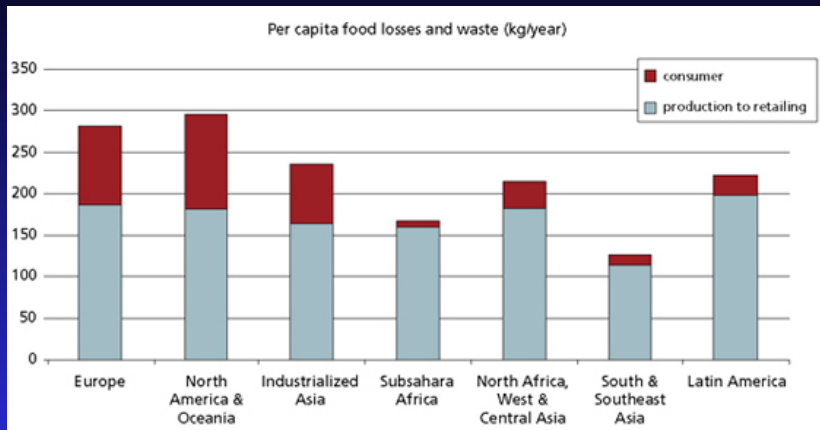
| THE SHELF LIFE OF FOOD  |                   |                    |                          |
|---|-------------------|--------------------|--------------------------|
| Foods unopened, uncut or uncooked unless stated otherwise                                       | COUNTER/PANTRY    | REFRIGERATOR       | FREEZER                  |
|   | 1 DAY ← → 1 MONTH | 1 DAY ← → 3 MONTHS | 1 MONTH ← → 1 YEAR       |
| <br>APPLES     | 2-4 weeks         | 1-2 months         | 8-12 months              |
| <br>BANANAS    | 2-7 days          | 5-9 days           | 2-3 months               |
| <br>CANTALOUPE | <u>Until ripe</u> | 1 week             | 8-12 months              |
| <br>CARROTS    | Up to 4 days      | 4-5 weeks          | 8-12 months              |
| <br>CUCUMBERS  | 1-3 days          | 1 week             | 8-12 months              |
| <br>EGGS       | Few hours         | 3-4 weeks          | Do not <del>freeze</del> |
| <br>MILK       | Few hours         | 5-7 days           | 1 month                  |
| <br>YOGURT     | Few hours         | 2-3 weeks          | 1-2 months               |

# Fascinating Facts About Food Perishability



Source: Food and Agriculture Organization of the United Nations 2011

# Wasting of Food



Source: Food and Agriculture Organization of the United Nations 2018

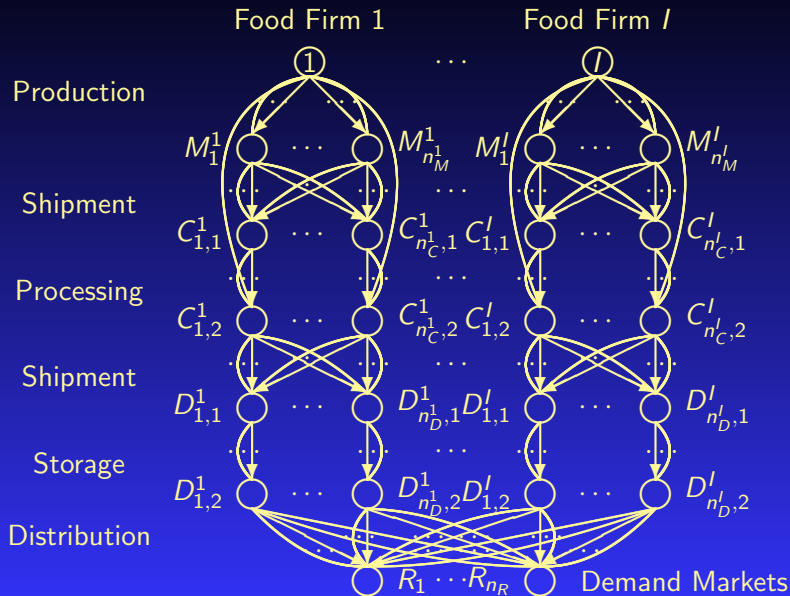
# Fresh Produce Food Supply Chains

Our fresh produce supply chain network oligopoly model:

1. captures the deterioration of fresh food along the entire supply chain from a network perspective;
2. handles the time decay through the introduction of arc multipliers;
3. formulates oligopolistic competition with product differentiation;
4. includes the disposal of the spoiled food products, along with the associated costs;
5. allows for the assessment of alternative technologies involved in each supply chain activity.

Reference: “Competitive Food Supply Chain Networks with Application to Fresh Produce,” M. Yu and A. Nagurney, *European Journal of Operational Research* **224(2)** (2013), pp 273-282.

# Fresh Produce Food Supply Chains



# Fresh Produce Food Supply Chains

Food products also deteriorate over time and especially fresh produce. According to Nahmias (1982), each unit has a probability of  $e^{\lambda t_a}$  of surviving  $t_a$  units of time where  $\lambda$  is the decay rate. Hence, arc multipliers can be constructed in a similar manner as those for the medical nuclear supply chain:

$$\alpha_a = e^{-\lambda t_a}$$

where  $\lambda$  is the decay rate for the food.

In rare cases, food deterioration follows the zero order reactions with linear decay (see Tijssens and Polderdijk (1996) and Rong, Akkerman, and Grunow (2011)). Then,

$$\alpha_a = 1 - \lambda t_a$$

for a post-production link.

# Pharmaceutical Supply Chains

The supply chain generalized network oligopoly model has the following novel features:

1. it handles the perishability of the pharmaceutical product through the introduction of arc multipliers;
2. it allows each firm to minimize the discarding cost of waste / perished medicine;
3. it captures product differentiation under oligopolistic competition through the branding of drugs, which can also include generics as distinct brands.

References can be found in our paper, “A Supply Chain Generalized Network Oligopoly Model for Pharmaceuticals Under Brand Differentiation and Perishability,” A.H. Masoumi, M. Yu, and A. Nagurney, *Transportation Research E* **48** (2012), pp 762-780.



# Pharmaceutical Supply Chains

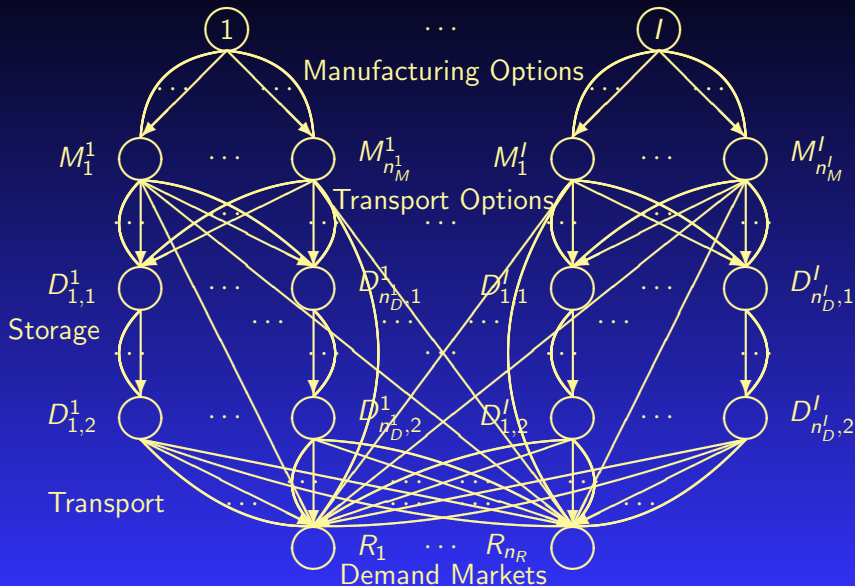
We consider  $I$  pharmaceutical firms, with a typical firm denoted by  $i$ .

The firms compete non-cooperatively, in an oligopolistic manner, and the consumers can differentiate among the products of the pharmaceutical firms through their individual product brands.

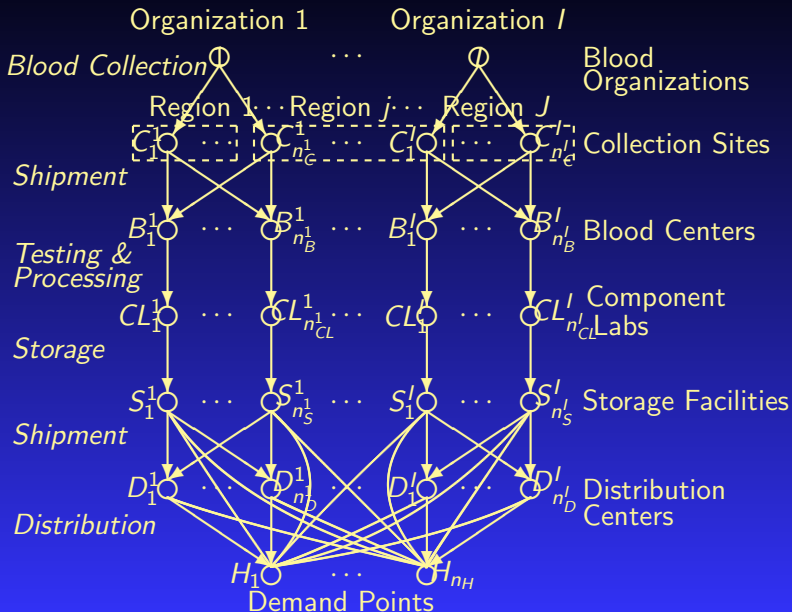
The supply chain network activities include manufacturing, shipment, storage, and, ultimately, the distribution of the brand name drugs to the demand markets.

Pharmaceutical Firm 1

Pharmaceutical Firm  $I$



# Blood Supply Chain Competition - Nagurney and Dutta (2019)



# Network Models and Disaster Relief

# Network Models Are Also Very Useful in Disaster Relief



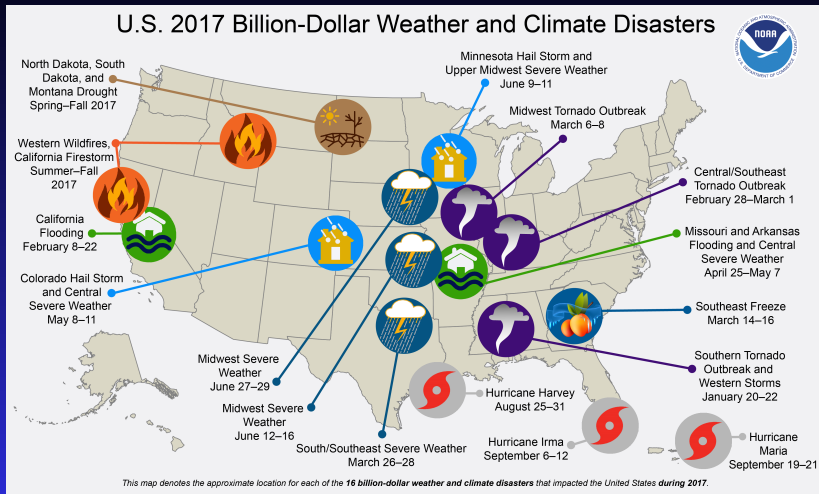
# Examples of Some Disasters

- The biggest blackout in North America, August 14, 2003;
- The Indonesian tsunami (and earthquake), December 26, 2004;
- Hurricane Katrina, August 23, 2005;
- 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;
- Superstorm Sandy, October 29, 2012;
- Hurricanes Harvey, Irma, and Maria that struck in 2017 and Hurricanes Florence and Michael in 2018.

# Hurricane Katrina, Fukushima, and Superstorm Sandy



# Billion Dollar Disasters in the United States in 2017



**2017 Set a Record for Losses in the US from Natural Disasters**



**Disasters have a catastrophic effect on human lives and a region's or even a nation's resources.**

# Natural Disasters and Colombia

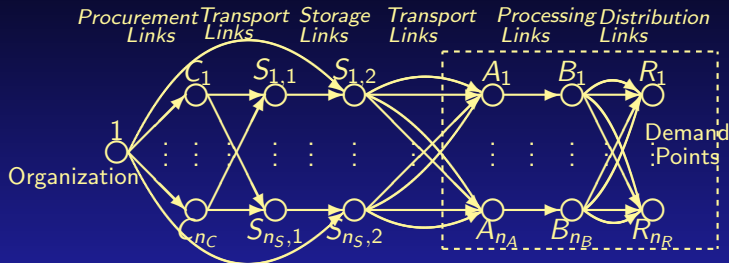
According to PrepareCenter.org, Colombia is widely recognized as one of the most disaster-prone countries in the world, with the World Bank reporting that at least 85% of its population and its assets are exposed to two or more natural hazards.



# Natural Disasters and Colombia

- This exposure is to both low-frequency/high-impact events (earthquakes, volcanic eruptions, Atlantic hurricanes) and to high-frequency/lower-impact events (floods and landslides).
- In response to its high risk profile, Colombian leaders are taking concrete actions to reduce vulnerability. **Colombia is now considered a role model in the Americas region for its progress in establishing a strong institutional and legal framework for disaster risk reduction through law 1523.**
- This law established a “National System for Disaster Risk Management,” putting into place national public policy not only for natural disaster response but also prevention.

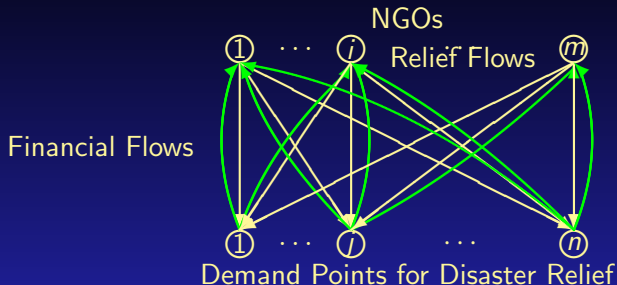
# Time in Disaster Relief



Network Topology of the Integrated Disaster Relief Supply Chain

A. Nagurney, A.H. Masoumi, and M. Yu, "An Integrated Disaster Relief Supply Chain Network Model with Time Targets and Demand Uncertainty." In: *Regional Science Matters: Studies Dedicated to Walter Isard*, P. Nijkamp, A. Rose, and K. Kourtit, Editors, Springer International Publishing Switzerland (2015), pp 287-318.

# A Game Theory Disaster Relief Model



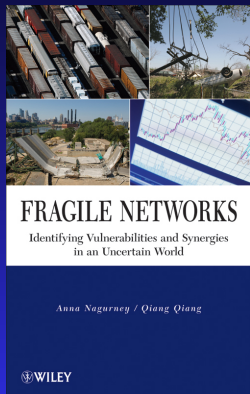
The Network Structure of an Integrated Game Theory Model

A. Nagurney et al., "A Variational Equilibrium Network Framework for Humanitarian Organizations in Disaster Relief: Effective Product Delivery Under Competition for Financial Funds." In: *Dynamics of Disasters: Algorithmic Approaches and Applications*, I.S. Kotsireas, A. Nagurney, and P.M. Pardalos, Editors, Springer International Publishers Switzerland (2018), pp 109-133.

# Cybercrime and Cybersecurity

# How I Became Interested in Cybersecurity

One of my books, written with a UMass Amherst PhD alum, was “hacked” and digital copies of it posted on websites around the globe.



In a sense, this may be viewed as a compliment since clearly someone had determined that it has some sort of *value*.

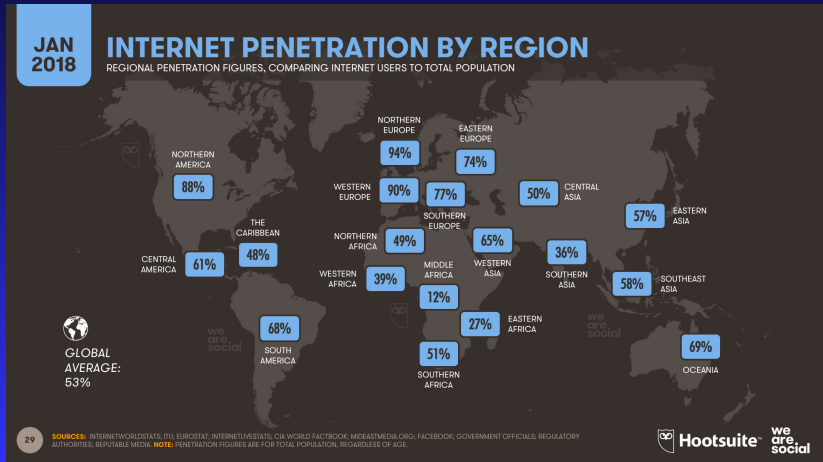
**The publisher John Wiley & Sons was notified and lawyers got involved but how do you contact and then influence those responsible for postings on rather anonymous websites?**

About the same time news about cyberattacks was getting prominent attention in the media and there were those interested in working with us on related research on cybersecurity.



**The Internet has transformed the ways** in which individuals, groups, organizations communicate, obtain information, access entertainment, and conduct their economic and social activities.

**In 2012, there were over 2.4 billion users. In 2019, the number of Internet users surpassed 4.3 billion users, more than half of the world's population.**



## Some Recent Major Cyberattacks

- **Equifax:** In September 2017, it was revealed that names, SSNs, birthdates, drivers' license information, and credit card numbers on about 143 million U.S. consumers was compromised in a cybersecurity breach that began in mid-May and was discovered only on July 29, 2017 (Bloomberg (2017)). In late February 2018, Equifax disclosed that it had discovered that an additional 2.4 million U.S. consumers were affected by the cyberattack (Reuters (2018)).



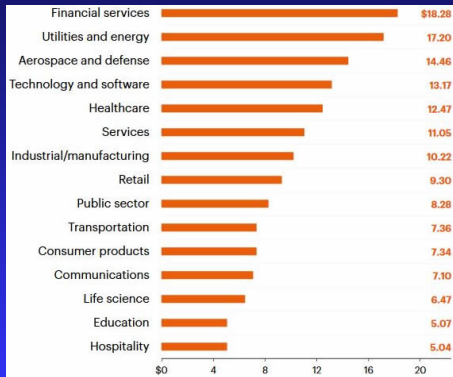
- **“WannaCry” ransomware:** Began in mid-May 2017. It crippled National Health Services (NHS) hospitals in the UK, hobbling emergency rooms, delaying vital medical procedures, and creating chaos (WIRED (2017)).

# Some Recent Major Cyberattacks

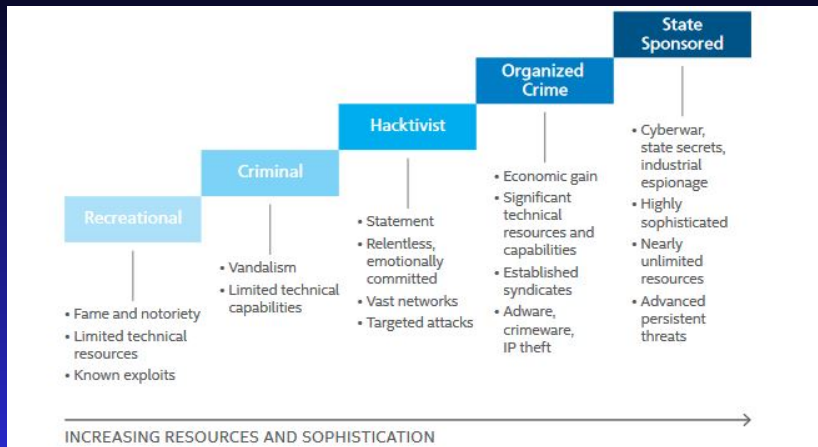
- **Banks:** The Carbanak group, also known as Anunak, was exposed in 2015 after supposedly stealing upwards of \$1 billion from more than 100 banks across 30 countries (The New York Times (2015)).
- **US Office of Personnel Management:** In June 2015, OPM discovered that sensitive information, including SSNs of 21.5 million federal employees was stolen (WIRED (2016)).
- **Sony Pictures Entertainment** The attack on Sony in 2014 destroyed data on more than 3,000 computers and disclosed prerelease films and embarrassing emails of executives (Fortune (2015)).
- **Target, Home Depot, Michaels Stores, Staples, and eBay:** These were breached in 2014 - card data and personal information of millions of customers were stolen (The New York Times (2015)).

# Cost of Cybercrime

- **Cybercrimes are costly for organizations.** According to Forbes (2017), cybercrime will cost the world about \$6 trillion per year on average through 2021. All industries fall victim to cybercrime, but to different degrees. **Average annual costs per company caused by global cybercrime as of 2017 by sector (in million US\$) (Ponemon(2017))**



# Changing Attacker Profiles



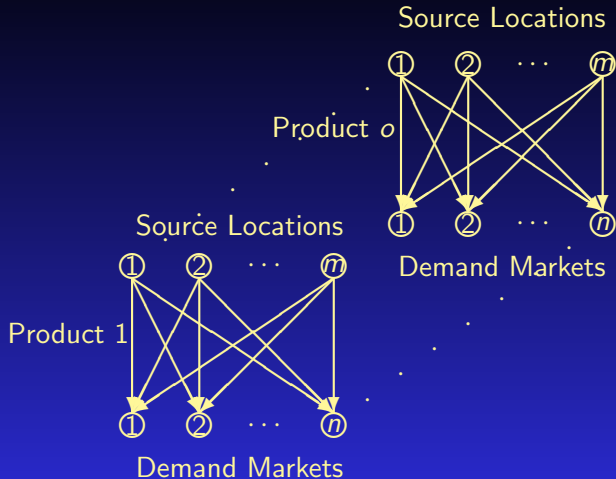
McAfee Labs Threats Report, August 2015

# Cybercrime

Clearly, hackers go where there is money.



# Perishability and Cybercrime in Financial Products



The model is constructed in the paper, "A Multiproduct Network Economic Model of Cybercrime in Financial Services," A. Nagurney, *Service Science* **7(1)** (2015), pp 70-81.

# Cybersecurity and Supply Chains



**Supply chains are also vulnerable to cyberattacks and can serve as entre points**



# Some Other Examples of Our Recent Cybersecurity Work

“Multifirm Models of Cybersecurity Investment Competition vs. Cooperation and Network Vulnerability,” A. Nagurney and S. Shukla, *European Journal of Operational Research* **260(2)** (2017), pp 588-600.

“A Supply Chain Network Game Theory Model of Cybersecurity Investments with Nonlinear Budget Constraints,” A. Nagurney, P. Daniele, and S. Shukla, *Annals of Operations Research* **248(1)** (2017), pp 405-427.

“Cybersecurity Investments with Nonlinear Budget Constraints: Analysis of the Marginal Expected Utilities,” P. Daniele, A. Maugeri, and A. Nagurney. In: *Operations Research, Engineering, and Cyber Security*, Th.M. Rassias and N.J. Daras (Eds.), Springer International Publishing Switzerland (2017), pp 117-134.

# Envisioning a New Kind of Internet – ChoiceNet

# Envisioning a New Kind of Internet – ChoiceNet



We were one of five teams funded by NSF as part of the Future Internet Architecture (FIA) project. Our project: *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
- ▶ RENC/UNC: Ilya Baldin
- ▶ University of Massachusetts Amherst: Tilman Wolf, Anna Nagurney

# Network Economic Conundrums and Operations Research to the Rescue

- **New architectures are focusing on networking technology, and not on economic interactions. Also, they lack in mechanisms to introduce competition and market forces.**
- Existing economic models cannot be deployed in today's Internet: **no mechanisms in order to create and discover contracts with any provider and to do so on short-time scales, and time-scales of different lengths.**
- We have developed multitiered network economic game theory models using **novel operations research methodologies**, including that of *projected dynamical systems* to study ChoiceNet and to explore the evolution of prices and flows among content and service providers.

# Designing an Internet



The new book by Clark, a developer of the Internet, cites our paper: “ChoiceNet: Toward an Economy Plane for the Internet,” Wolf, Griffioen, Calvert, Dutta, Rouskas, Baldin, and Nagurney, *ACM SIGCOMM Computer Communication Review* **44(3)** (2018), pp 58-65.

# ChoiceNet Goals

- **Expose choices throughout the network**
  - Network is no longer a “black box”
- **Interactions between technological alternatives and relationships** – Introduction of a dynamic “economy plane”
  - Money as a driver to overcome inertia by providers
  - Market forces can play out within the network itself
- **Services are at the core of ChoiceNet – “everything is a service”**
  - Services provide a benefit but entail a cost
  - Services are created, composed, sold, verified, etc.

The focus of ChoiceNet is on *choices* and *network economics*.  
Choice criteria can also include privacy, minimization of risk, even environmental impact minimization.

**Transparency associated with ChoiceNet and having more refined routing options can also aid in cybersecurity.**

# ChoiceNet Principles

*Competition Drives Innovation!*

**Services are at core of ChoiceNet**

(“everything is a service”)

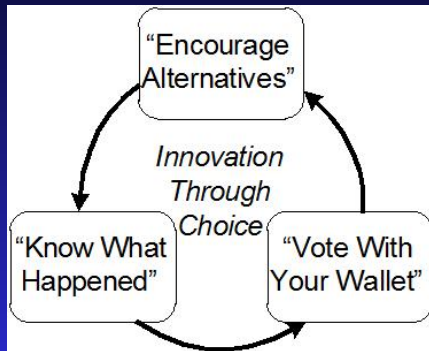
Services provide a benefit, have a cost

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

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

**“Know what happened”** Ability to evaluate services

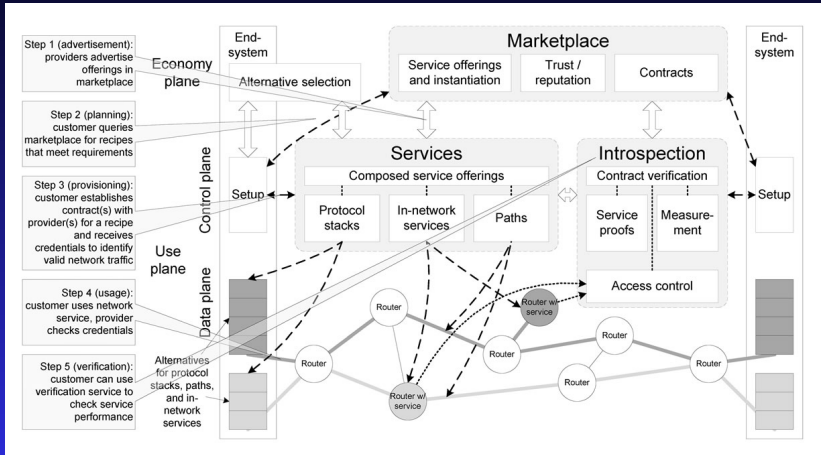
**“Vote with your wallet”** Reward good services!





- **ChoiceNet enables the composition of services and economic relationships**
  - Economy plane: customer-provider relationships
  - Use plane: client-service relationships
  - Positive feature is the ability to reflect real-world relationships.

# ChoiceNet Architecture



# Use Cases Enabled by ChoiceNet

- **ChoiceNet / economy plane enables new business models in the Internet**

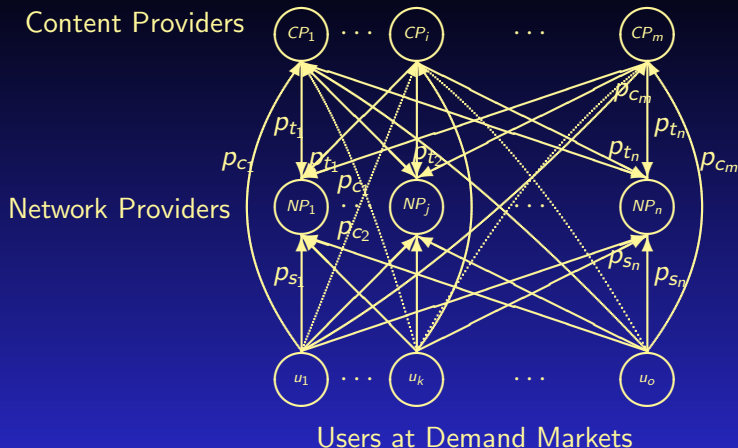
- Very dynamic economic relationships are possible
- All entities get rewarded.

- **Examples**

- Movie streaming
- Reading *The New York Times* or *The Boston Globe* in a coffee shop (short-term and long-term contracts)
- Customers as providers.




# Game Theory Models - Flow of Content and Payments




“A Network Economic Game Theory Model of a Service-Oriented Internet with Price and Quality Competition in Both Content and Network Provision,” S. Saberi, A. Nagurney, and T. Wolf, *Service Science* **6(4)** (2014), pp 229-250.

# Muchas gracias!




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**The Virtual Center for Supernetworks** is an interdisciplinary center at the Isenberg School of Management that advances knowledge on large-scale networks and integrates operations research and management science, engineering, and economics. Its Director is Dr. Anna Nagurney, the John F. Smith Memorial Professor of Operations Management.

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