Networks to Save the World:
OR in Action

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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

When were you first captivated by OR?

From my first course at Brown University on the subject to my first projects in industry - working in the high tech defense sector on naval submarines in Newport, Rhode Island, I was drawn to the power of the subject, especially when combined with computing.

Off to Grad School for a PhD

Very soon I realized that I did not like having a boss!

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.

EQUILIBRIUM MODELING, ANALYSIS AND COMPUTATION: THE CONTRIBUTIONS OF STELLA DAFERMOS

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(Received June 1990; accepted August 1990)

This memorial tribute to the late Stella Dafermos summarizes her contributions to equilibrium modeling, analysis, and computation, and provides a list of her published papers.

On April 5, 1990, with the death at 49 of Stella Dafermos, Professor of Applied Mathematics and Engineering at Brown University, Providence, Rhode Island, the operations research community lost one of its early woman doctorates. Throughout her quarter-century career she dedicated herself to developing rigorous mathematical formalisms for modeling, analyzing and making computations related to competitive equilibrium systems that spanned applications from congested urban transportation networks to multicommodity trade. Beginning with her 1968 doctoral dissertation, "Traffic Assignment and Resource Allocation in Transportation Networks," directed by F. T. Sparrow at Johns Hopkins University, which focused on the study of system-optimized and user-optimized transportation networks, she initiated a theme of advancement of methodologies by which the behavior of complex systems could be captured and studied.

EQUILIBRIUM MODELING

In her first paper, based on her thesis and published in 1969, she proposed convergent equilibration algorithms that simulated the adjustment behavior of travelers on a congested network operating in their own self-interest in choosing their routes. The governing equilibrium conditions, due to Wardrop, reflected that only the minimum cost routes connecting each origin/destination pair would be used. These algorithms took advantage of the problem structure and were later extended in papers published in 1971 and 1972 to network models that allowed for interaction among users of the system via the link cost functions. In her 1969 paper she also focused on stability issues, which began the theme of qualitative analysis of equilibrium patterns that was also to pervade her scholarly work.

These network equilibrium models, as well as the integrated models that allowed for both location and route choice, developed in her paper of 1976, were formulated as optimization problems, with the observation that the equilibrium conditions governing these problems were actually the Kuhn-Tucker conditions of an appropriately constructed optimization problem. Interestingly, parallel to these developments in nonlinear networks, the economics community was reformulating spatial price equilibrium problems, in which commodities are produced, consumed and traded, subject to transportation or transaction costs, as optimization problems. However, the assumption required for such a transformation—that of *symmetry*, in which cross-effects of various interactions had to be identical—precluded the realistic modeling of multiple modes of transportation and different classes of users of a given system, as well as multiple commodities. Moreover, the objective function thus constructed, although convenient and essential given the state-of-the-art at the time, was artificial. Furthermore, equilibrium problems, by their very nature, involve more than a single agent and objective function, with interactions among the agents, and, hence, the objective functions being the rule rather than the exception. To overcome such shortcomings, a methodological advance was needed.

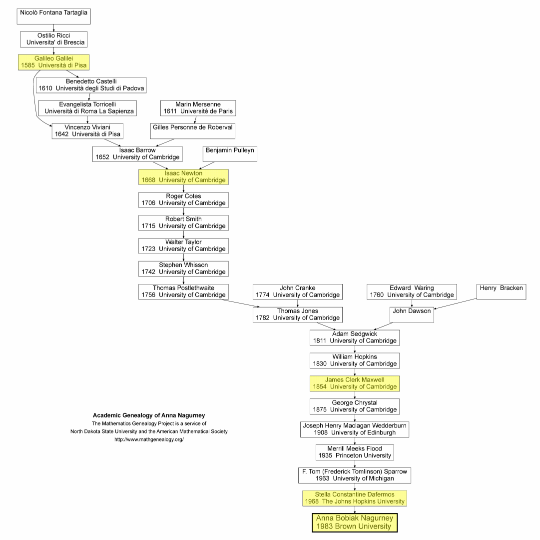
In 1980 Stella made a fundamental discovery by observing that the equilibrium conditions of the traffic assignment problem actually had the structure of a variational inequality problem. Although the theory of variational inequalities had been introduced over a decade earlier for the study of partial differential equations, the emphasis there was on infinite-dimensional problems arising in mechanics, and its use as a powerful tool for equilibrium analysis in operations research was left unrealized. Stella's identification of network equilibrium conditions with a variational inequality problem opened up new horizons for mathematical modeling, analysis and the efficient computation of more general equilibrium systems than had heretofore been possible. With this

Subject classifications: Economics: solution of equilibrium problems. Networks/graphs: equilibrium modeling and computation. Transportation: formulation and solution of multimodal problems.

Operations Research
Vol. 39, No. 1, January-February 1991 9
0030-364X/91/3901-0008 $01.25

Stella was only the second female to have received a PhD in OR and that was at Johns Hopkins University.

On the Shoulders of Giants - Academic Genealogy



Our Fabulous **OR** Community

After I received my PhD, I met **Professor George Dantzig of Stanford University**, the developer of the simplex method and a Father of OR! He came to the first presentation that I ever gave, post PhD, at the Mathematical Programming Symposium at MIT.

A Brief History of the Science of Networks

1736 - Euler - the earliest paper on graph theory - Königsberg bridges problem.

1758 - Quesnay in his *Tableau Economique* introduced a graph to depict the circular flow of financial funds in an economy.

1781 - Monge, who had worked under Napoleon Bonaparte, publishes what is probably the first paper on transportation in minimizing cost.

1838 - Cournot states that a competitive price is determined by the intersection of supply and demand curves in the context of spatially separate markets in which transportation costs are included.

1841 - Kohl considered a two node, two route transportation network problem.

A Brief History of the Science of Networks

1845 - Kirchhoff wrote Laws of Closed Electric Circuits.

1920 - Pigou studied a transportation network system of two routes and noted that the decision-making behavior of the users on the network would result in different flow patterns.

1936 - König published the first book on graph theory.

1939, 1941, 1947 - Kantorovich, Hitchcock, and Koopmans considered the network flow problem associated with the classical minimum cost transportation problem and provided insights into the special network structure of these problems, which yielded special-purpose algorithms.

A Brief History of the Science of Networks

1948, 1951 - Dantzig published the simplex method for linear programming and adapted it for the classical transportation problem.

1951 - Enke showed that spatial price equilibrium problems can be solved using electronic circuits

1952 - Copeland in his book asked, Does money flow like water or electricity?

1952 - Samuelson gave a rigorous mathematical formulation of spatial price equilibrium and emphasized the network structure.

A Brief History of the Science of Networks

1956 - Beckmann, McGuire, and Winsten in their book, *Studies in the Economics of Transportation*, provided a rigorous treatment of congested urban transportation systems under different behavioral mechanisms due to Wardrop (1952).

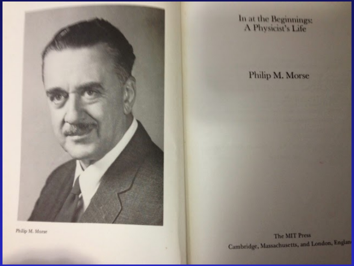
1962 - Ford and Fulkerson's book *Flows in Networks* is published.

1969 - Dafermos and Sparrow coined the terms user-optimization and system-optimization and develop algorithms for the computation of solutions that exploit the network structure of transportation problems.

1993 - Ahuja, Magnanti, and Orlin's book *Network Flows: Theory, Algorithms, and Applications* is published.

A Few Quotes

Philip M. Morse in his 1977 book, “In at the Beginnings” writes: *The delights of research in O/R are multiple. To me the pleasure coming from understanding how traffic behaves is as great as that coming from understanding how two atoms combine. In addition, the practical applications of O/R theory are often immediate and satisfying.*



He ends his book with: *For those who like exploration, immersion in scientific research is not unsocial, is not dehumanizing; in fact, it is a lot of fun. And, in the end, if one is willing to grasp the opportunities, it can enable one to contribute something to human welfare*.

Some of the Biggest Global Challenges

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

- climate change
- food security
- healthcare
- future of the Internet
- rising income inequality.

Network Systems and the Braess Paradox

I Work on the Modeling of Network Systems

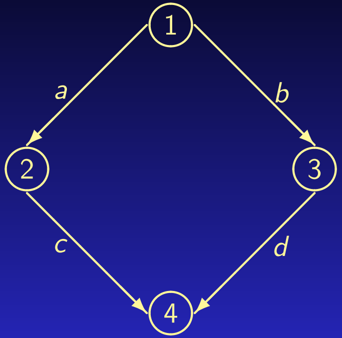
And utilize optimization, game theory, and also dynamical systems to gain insights as to the behavior of stakeholders.

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



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

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

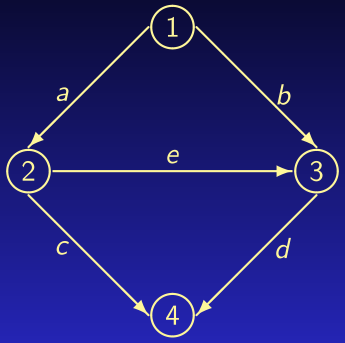
Adding a Link Increases Travel Cost for All!

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 1968 Braess article has been translated from German to English:

"On a Paradox of Traffic Planning,"

D. Braess, A. Nagurney, and T. Wakolbinger, *Transportation Science* **39** (2005), pp 446-450.

Über ein Paradoxon aus der Verkehrsplanung

Von D. Braess, Münster [1])

Eingegangen am 28. März 1968

Zusammenfassung: Für die Straßenverkehrsplanung möchte man den Verkehrsfluß auf den einzelnen Straßen des Netzes abschätzen, wenn die Zahl der Fahrzeuge bekannt ist, die zwischen den einzelnen Punkten des Straßennetzes verkehren. Welche Wege am günstigsten sind, hängt nun nicht nur von der Beschaffenheit der Straße ab, sondern auch von der Verkehrsdichte. Es ergeben sich nicht immer optimale Fahrzeiten, wenn jeder Fahrer nur für sich den günstigsten Weg heraussucht. In einigen Fällen kann sich durch Erweiterung des Netzes der Verkehrsfluß sogar so umlagern, daß größere Fahrzeiten erforderlich werden.

Summary: For each point of a road network let be given the number of cars starting from it, and the destination of the cars. Under these conditions one wishes to estimate the distribution of the traffic flow. Whether a street is preferable to another one depends not only upon the quality of the road but also upon the density of the flow. If every driver takes that path which looks most favorable to him, the resultant running times need not be minimal. Furthermore it is indicated by an example that an extension of the road network may cause a redistribution of the traffic which results in longer individual running times.

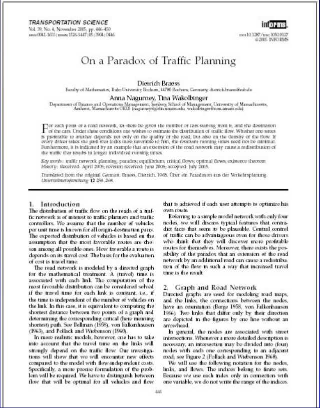
1. Einleitung

Für die Verkehrsplanung und Verkehrssteuerung interessiert, wie sich der Fahrzeugstrom auf die einzelnen Straßen des Verkehrsnetzes verteilt. Bekannt sei dabei die Anzahl der Fahrzeuge für alle Ausgangs- und Zielpunkte. Bei der Berechnung wird davon ausgegangen, daß von den möglichen Wegen jeweils der günstigste gewählt wird. Wie günstig ein Weg ist, richtet sich nach dem Aufwand, der zum Durchfahren nötig ist. Die Grundlage für die Bewertung des Aufwandes bildet die Fahrzeit.

Für die mathematische Behandlung wird das Straßennetz durch einen gerichteten Graphen beschrieben. Zur Charakterisierung der Bögen gehört die Angabe des Zeitaufwandes. Die Bestimmung der günstigen Stromverteilungen kann als gelöst betrachtet werden, wenn die Bewertung konstant ist, d. h., wenn die Fahrzeiten unabhängig von der Größe des Verkehrsflusses sind. Sie ist dann äquivalent mit der bekannten Aufgabe, den kürzesten Abstand zweier Punkte eines Graphen und den zugehörigen kritischen Pfad zu bestimmen [1], [5], [7].

Will man das Modell aber realistischer gestalten, ist zu berücksichtigen, daß die benötigte Zeit stark von der Stärke des Verkehrs abhängt. Wie die folgenden Untersuchungen zeigen, ergeben sich dann gegenüber dem Modell mit konstanter (belastungsunabhängiger) Bewertung z. T. völlig neue Aspekte. Dabei erweist sich schon eine Präzisierung der Problemstellung als notwendig; denn es ist zwischen dem Strom zu unterscheiden, der für alle am günstigsten ist,, und dem, der sich einstellt, wenn jeder Fahrer nur seinen eigenen Weg optimalisiert.

[1]) Priv.-Doz. Dr. Dietrich Braess, Institut für numerische und instrumentelle Mathematik, 44 Münster, Hüfferstr. 3 a.



TRANSPORTATION SCIENCE
Vol. 39, No. 4, November 2005, pp. 446–450

On a Paradox of Traffic Planning

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For each point of a road network, let there be given the number of cars starting from it, and the destination of the cars. Under these conditions one wishes to estimate the distribution of traffic flow. Whether one street is preferable to another depends not only on the quality of the road, but also on the density of the flow. If every driver takes the path that looks most favorable to him, the resultant running times need not be minimal. Furthermore, it is indicated by an example that an extension of the road network may cause a redistribution of the traffic that results in longer individual running times.

Key words: traffic network planning; paradox; equilibrium; critical flows; optimal flows; existence theorem
History: Received: April 2005; revision received: June 2005; accepted: July 2005.

Translated from the original German: Braess, Dietrich. 1968. Über ein Paradoxon aus der Verkehrsplanung. *Unternehmensforschung* **12** 258–268.

1. Introduction

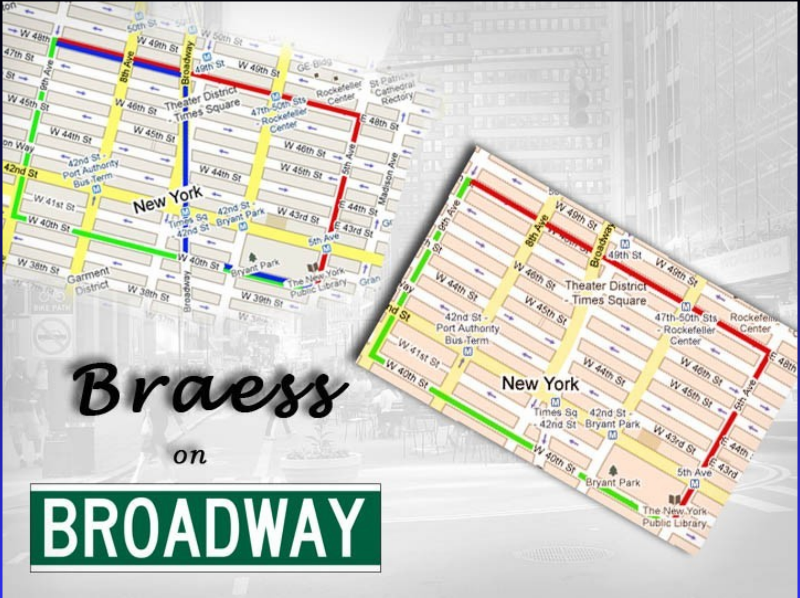
The distribution of traffic flow on the roads of a traffic network is of interest to traffic planners and traffic ...

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^{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.

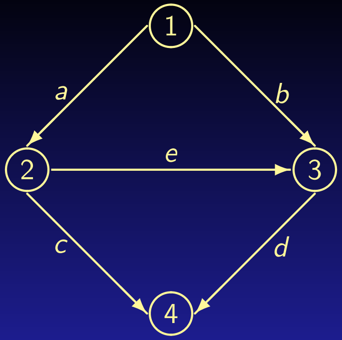


Braess
on
BROADWAY

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

Under 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.

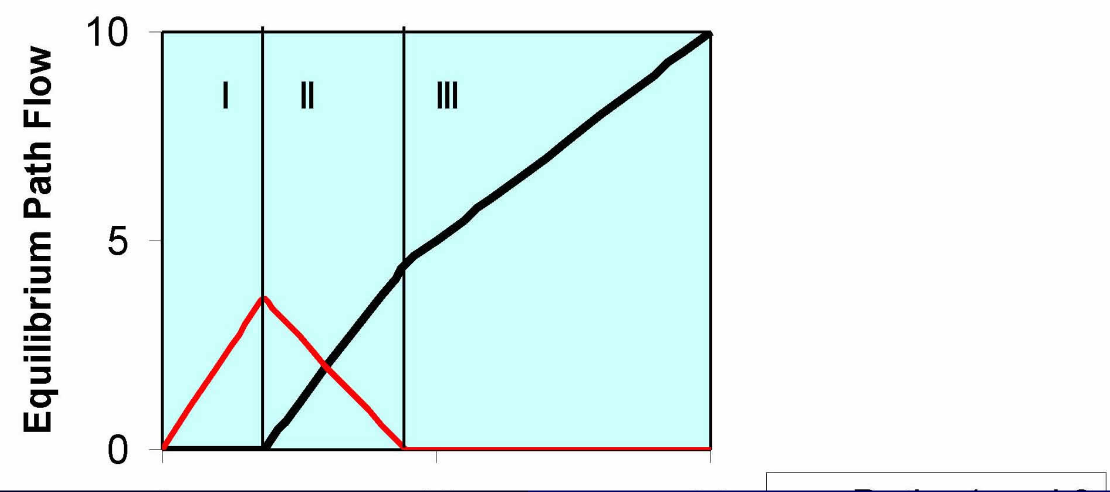
The Braess paradox never occurs in S-O networks.



Recall the Braess network with the added link e.

What happens as the demand increases?

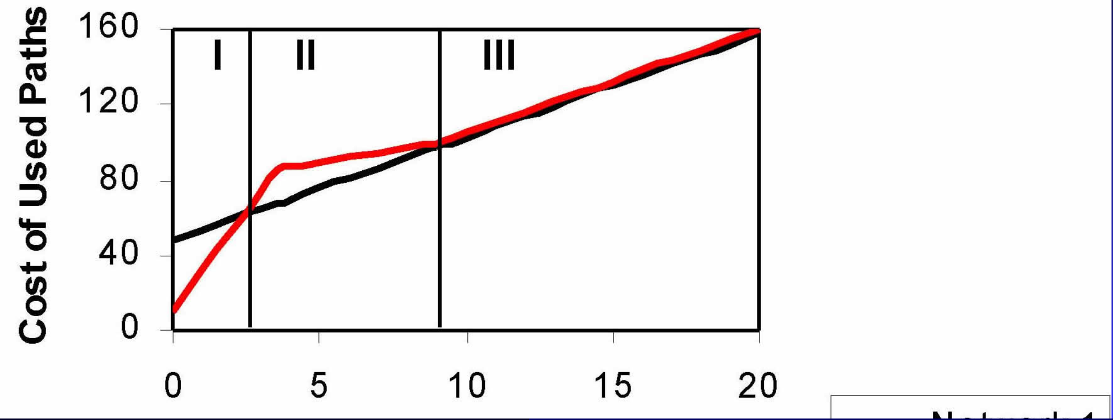
The U-O Solution of the Braess Network with Added Link (Path) and Time-Varying Demands Solved as an *Evolutionary Variational Inequality* (A. Nagurney, P. Daniele, and D. Parkes, *Computational Management Science* **4** (2007), pp 355-375).



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

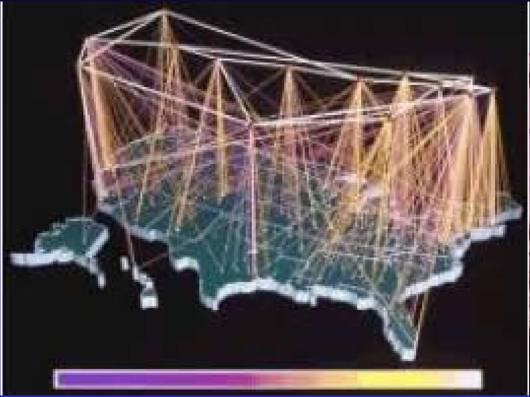
In Demand Regime II, the travel demand lies in the range [2.58, 8.89], and *the Addition of a New Link (Path) Makes Everyone Worse Off*!

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, $\mathrm{VI}(F, \mathcal{K})$*, 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.

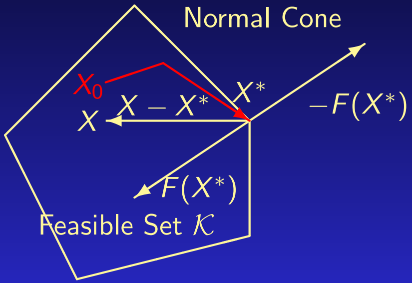
The variational inequality problem contains, as special cases, such mathematical programming problems as:

- 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 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)

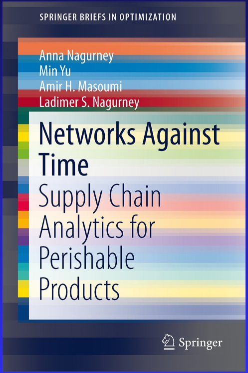
dynamic spectrum model for cognitive radio networks (Setoodeh, Haykin, and Moghadam (2012)).

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.

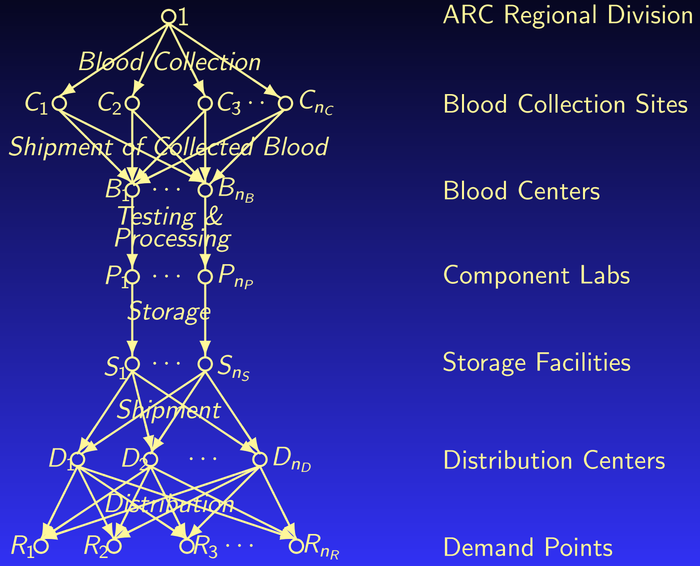
Blood Supply Chains for the Red Cross

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.

American Red Cross
Together, we can save a life

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.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Blood Collection
C_1 C_2 C_3 ··· C_{n_C}
Shipment of Collected Blood
B_1 ··· B_{n_B}
Testing &
Processing
P_1 ··· P_{n_P}
Storage
S_1 ··· S_{n_S}
Shipment
D_1 D_2 ··· D_{n_D}
Distribution
R_1 R_2 R_3 ··· R_{n_R}
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.

Medical Nuclear Supply Chains

We developed a medical nuclear supply chain network design model which captures the decay of the radioisotope molybdenum.

"Medical Nuclear Supply Chain Design: A Tractable Network Model and Computational Approach," A. Nagurney and L.S. Nagurney, *International Journal of Production Economics* **140(2)** (2012), pp 865-874.

Medical Nuclear Supply Chains

Medical nuclear supply chains are essential supply chains in healthcare and provide the conduits for products used in nuclear medical imaging, which is routinely utilized by physicians for diagnostic analysis for both cancer and cardiac problems.

Such supply chains have unique features and characteristics due to the products' time-sensitivity, along with their hazardous nature.

Salient Features:

- complexity
- economic aspects
- underlying physics of radioactive decay
- importance of considering both waste management and risk management.

Medical Nuclear Supply Chains

Over **10,000** hospitals in the world use radioisotopes (World Nuclear Association (2018)).

Technetium, ^{99m}Tc, which is a decay product of Molybdenum-99, ^{99}Mo, is the most commonly used medical radioisotope, used in more than 80% of the radioisotope injections, with more than 30 million procedures worldwide each year.

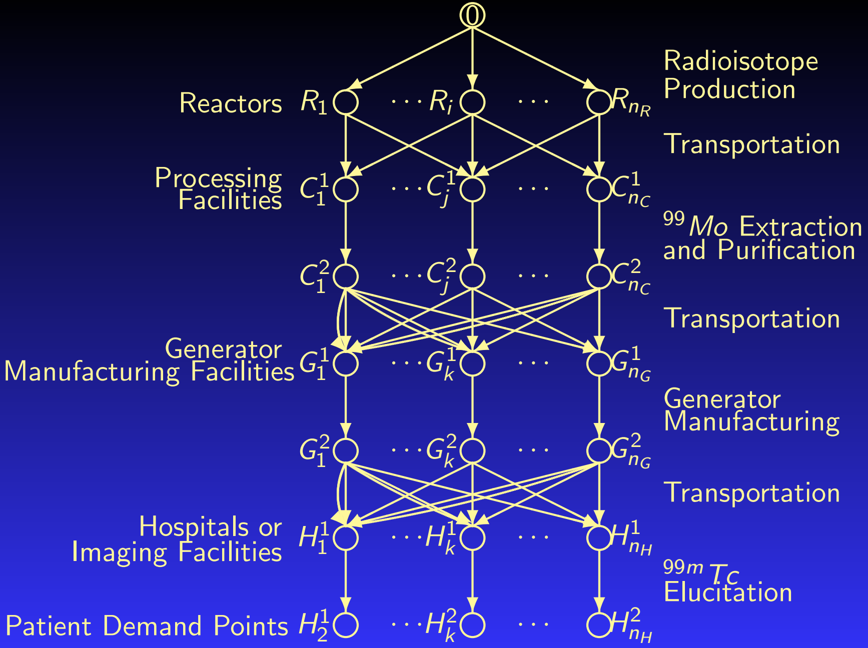
The half-life of Molybdenum-99 is 66 hours.

Each day, more than **40,000** nuclear medical procedures are performed in the United States using Technetium-99m.

Medical Nuclear Supply Chains

For over two decades, all of the Molybdenum necessary for US-based nuclear medical diagnostic procedures has come from **foreign** sources.

The majority of the reactors are between **40 and 50 years old**. Several of the reactors currently used are due to be retired by the end of this decade (Seeverens (2010) and OECD Nuclear Energy Agency (2010a)).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Radioisotope Production
Reactors R_1 $\cdots R_i$ $\cdots$ R_{n_R}
Transportation
Processing Facilities C_1^1 $\cdots C_j^1$ $\cdots$ $C_{n_C}^1$
^{99}Mo Extraction and Purification
C_1^2 $\cdots C_j^2$ $\cdots$ $C_{n_C}^2$
Transportation
Generator Manufacturing Facilities G_1^1 $\cdots G_k^1$ $\cdots$ $G_{n_G}^1$
Generator Manufacturing
G_1^2 $\cdots G_k^2$ $\cdots$ $G_{n_G}^2$
Transportation
Hospitals or Imaging Facilities H_1^1 $\cdots H_k^1$ $\cdots$ $H_{n_H}^1$
^{99m}Tc Elucitation
Patient Demand Points H_2^1 $\cdots H_k^2$ $\cdots$ $H_{n_H}^2$

Arc Multipliers

Because of the exponential decay of molybdenum, we have that the quantity of the radioisotope:

$$N(t) = N_0 e^{-\lambda t}$$

so that an arc multiplier on a link a that takes t_a hours of time corresponds to:

$$\alpha_a = e^{-\frac{ln2}{66.7} t_a}.$$

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 anther, 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.

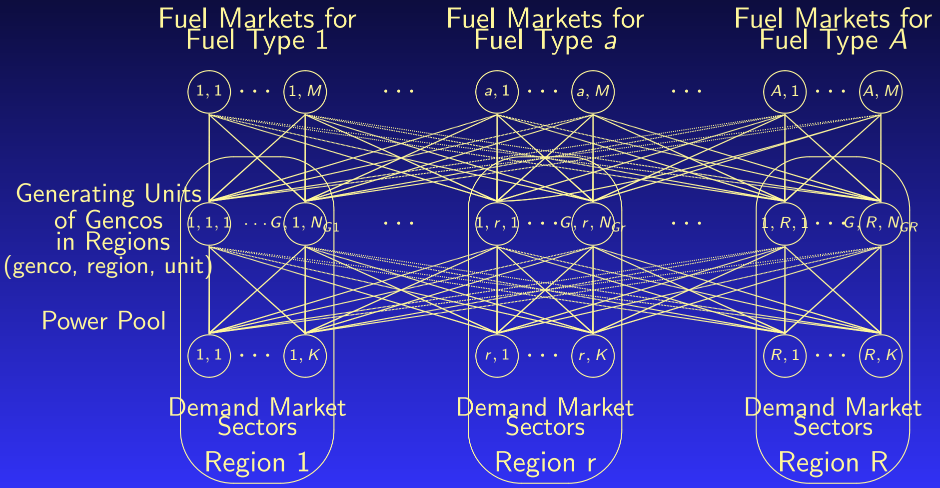
An Empirical Example of an Electric Power Supply Chain for New England

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

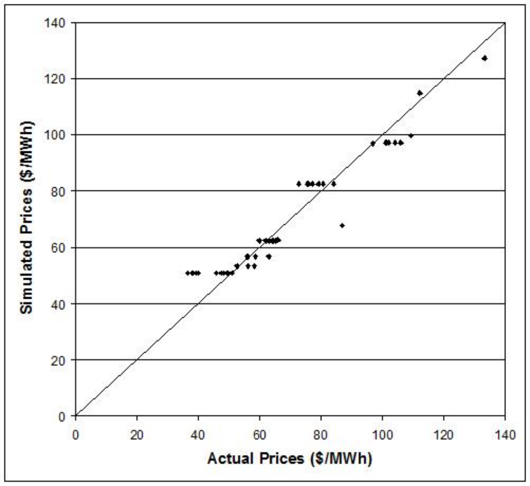
The Electric Power Supply Chain Network with Fuel Supply Markets



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; $w = 2, ..., 6$) 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)



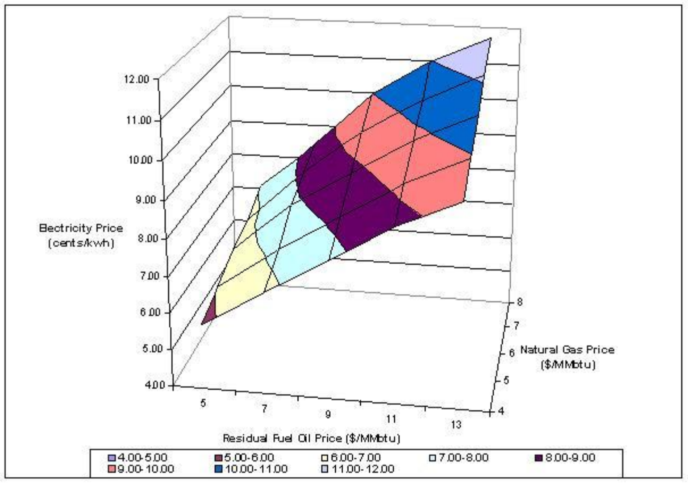
Sensitivity Analysis

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

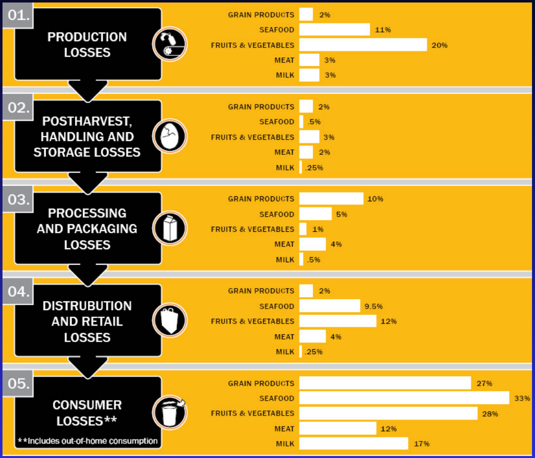
Food is something anyone can relate to.

Fascinating Facts About Food Perishability

THE SHELF LIFE OF FOOD

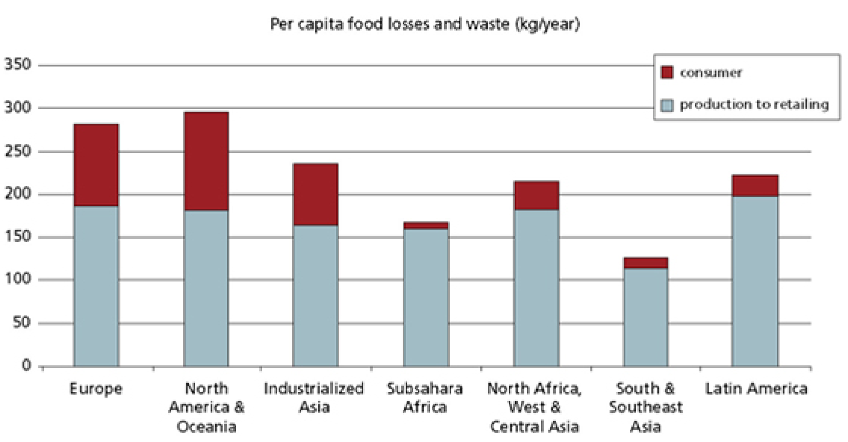
Foods unopened, uncut or uncooked unless stated otherwise	COUNTER/PANTRY (1 DAY → 1 MONTH)	REFRIGERATOR (1 DAY → 3 MONTHS)	FREEZER (1 MONTH → 1 YEAR)
APPLES	2-4 weeks	1-2 months	8-12 months
BANANAS	2-7 days	5-9 days	2-3 months
CANTALOUPE	Until ripe	1 week	8-12 months
CARROTS	Up to 4 days	4-5 weeks	8-12 months
CUCUMBERS	1-3 days	1 week	8-12 months
EGGS	Few hours	3-4 weeks	Do not freeze
MILK	Few hours	5-7 days	1 month
YOGURT	Few hours	2-3 weeks	1-2 months
BACON	2 hours	2 weeks	4 months
BOLOGNA	2 hours	1-2 weeks	2-3 months
CHICKEN	2 hours	1-2 days	1 year
FISH	2 hours	1-2 days	6-9 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

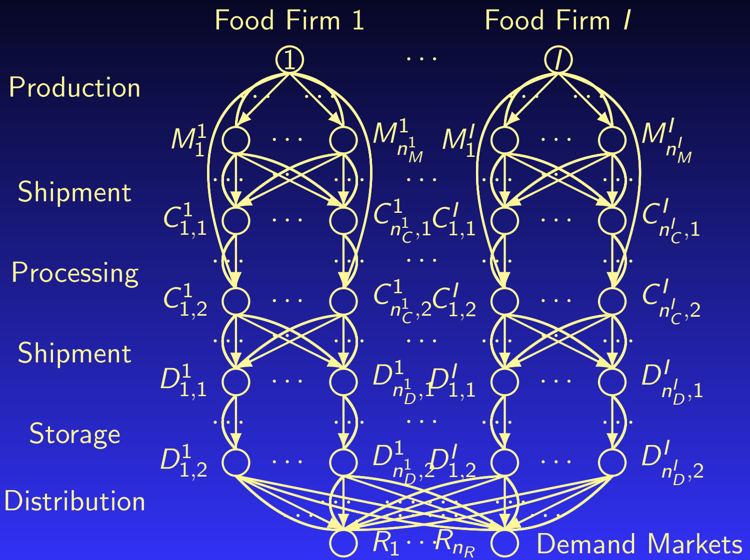
Fresh Produce Food Supply Chains

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 λ 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 λ is the decay rate for the food.

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

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

for a post-production link.

Pharmaceutical Supply Chains

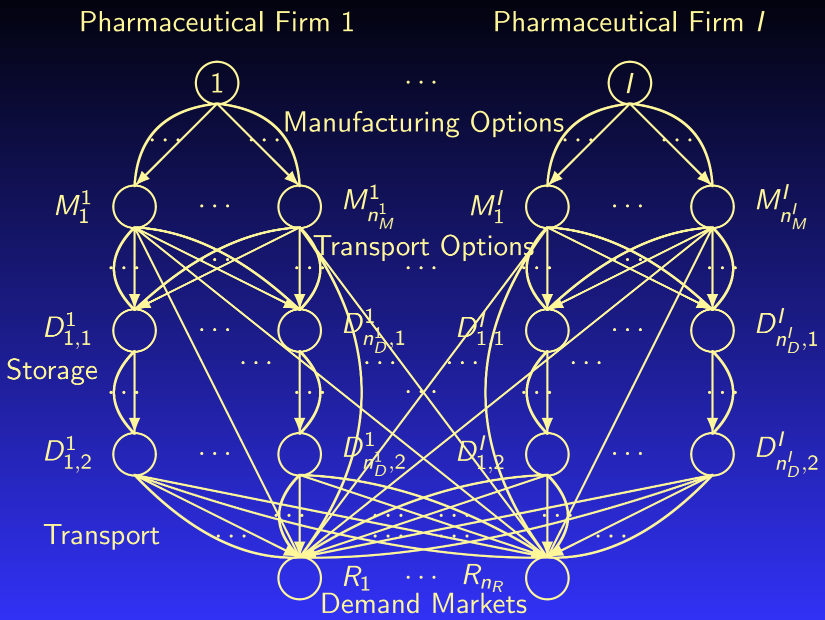
The supply chain generalized network oligopoly model has the following novel features:

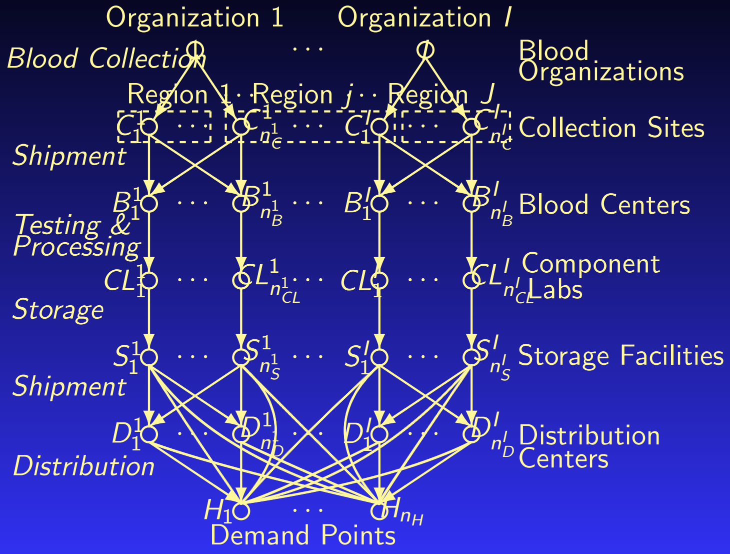
1. it handles the perishability of the pharmaceutical product through the introduction of arc multipliers;

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 Firm 1
Pharmaceutical Firm I
1
I
Manufacturing Options
M_1^1
$M_{n_M^1}^1$
M_1^I
$M_{n_M^I}^I$
Transport Options
$D_{1,1}^1$
$D_{n_D^1,1}^1$
$D_{1,1}^I$
$D_{n_D^I,1}^I$
Storage
$D_{1,2}^1$
$D_{n_D^1,2}^1$
$D_{1,2}^I$
$D_{n_D^I,2}^I$
Transport
R_1
R_{n_R}
Demand Markets


Organization 1
Organization I
Blood Collection
Blood Organizations
Region 1
Region j
Region J
Collection Sites
Shipment
Blood Centers
Testing & Processing
Component Labs
Storage
Storage Facilities
Shipment
Distribution Centers
Distribution
Demand Points

Network Models and Disaster Relief

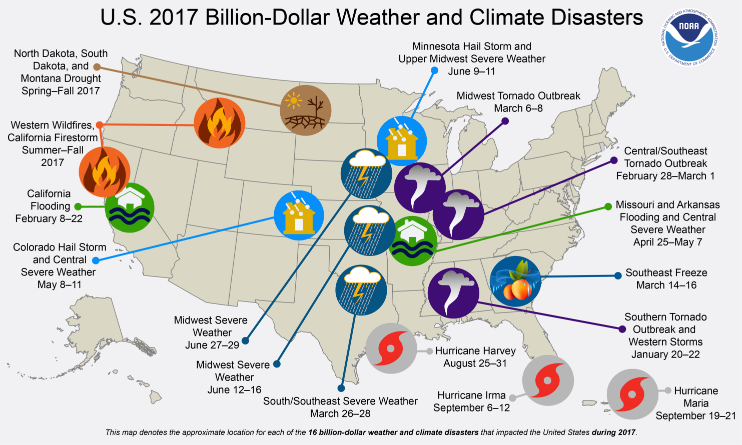
Network Models Are Also Very Useful in Disaster Relief

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.

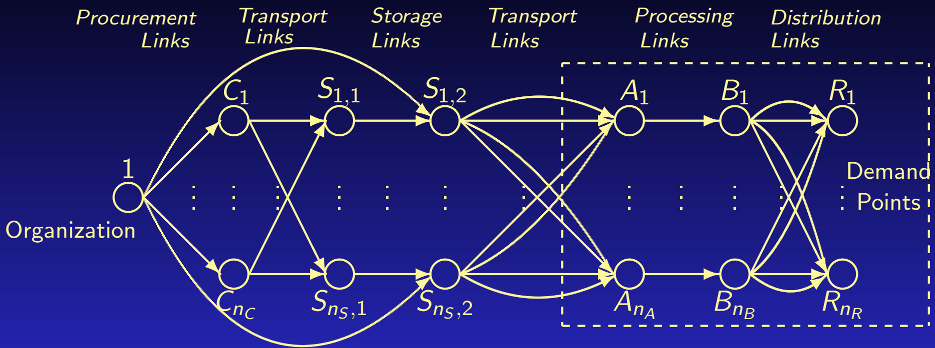
Hurricane Katrina, Fukushima, and Superstorm Sandy

Billion Dollar Disasters in the United States in 2017



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

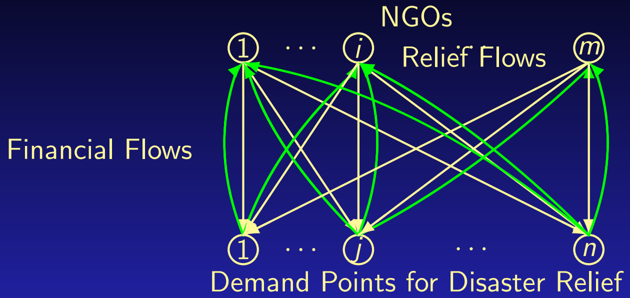
Time in Disaster Relief



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



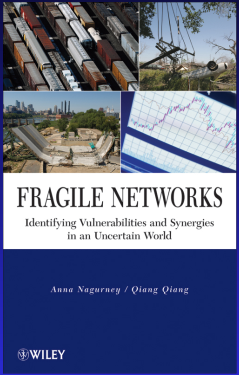
The Network Structure of an Integrated Game Theory Model

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.



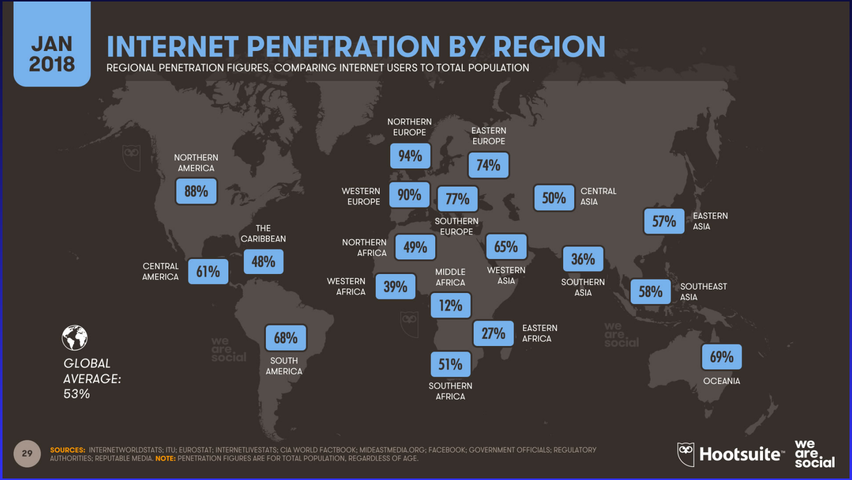
In a sense, this may be viewed as a compliment since clearly someone had determined that it has some sort of *value*.

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 2018, the number of Internet users has surpassed 4 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)).

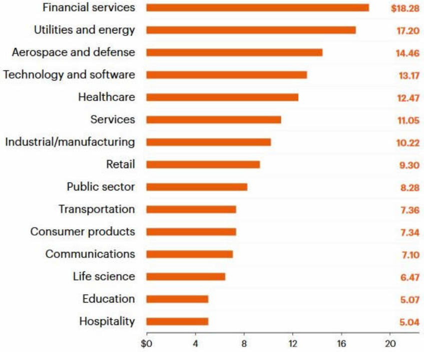
• **US Office of Personnel Management:** In June 2015, OPM discovered that sensitive information, including SSNs of 21.5 million federal employees was stolen (WIRED (2016)).

•**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)).

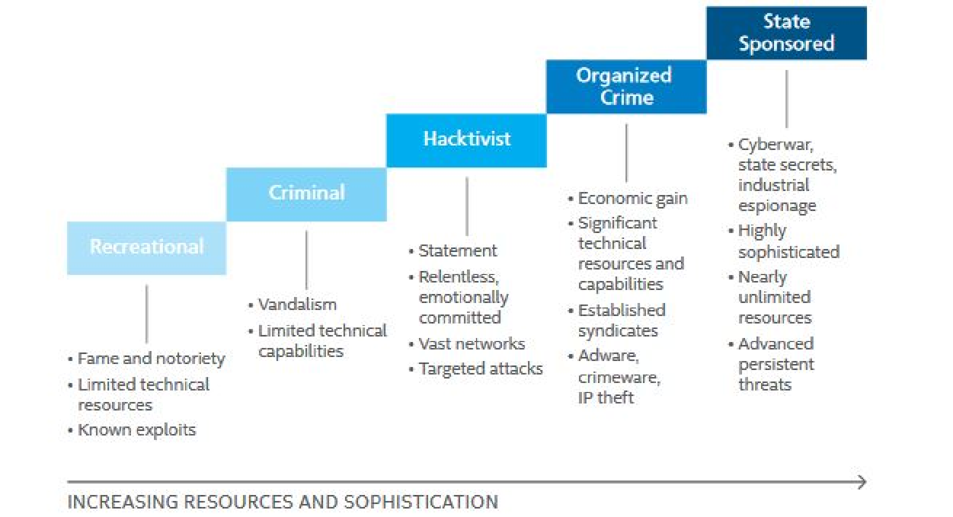
•**Target, Home Depot, Michaels Stores, Staples, and eBay:** These were breached in 2014 - card data and personal information of millions of customers were stolen (The New York Times (2015)).

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))**



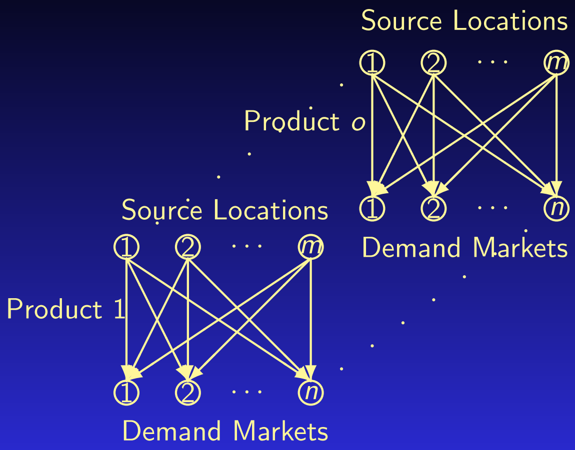
Changing Attacker Profiles



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
- RENCI/UNC: Ilya Baldin
- University of Massachusetts Amherst: Tilman Wolf, Anna Nagurney

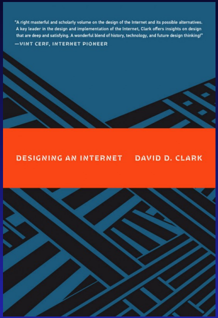
Network Economic Conundrums and Operations Research to the Rescue

- **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!

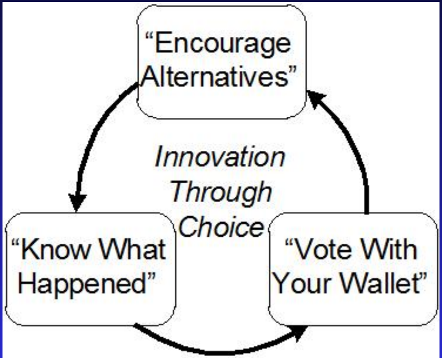
Services are at core of ChoiceNet ("everything is a service")

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!

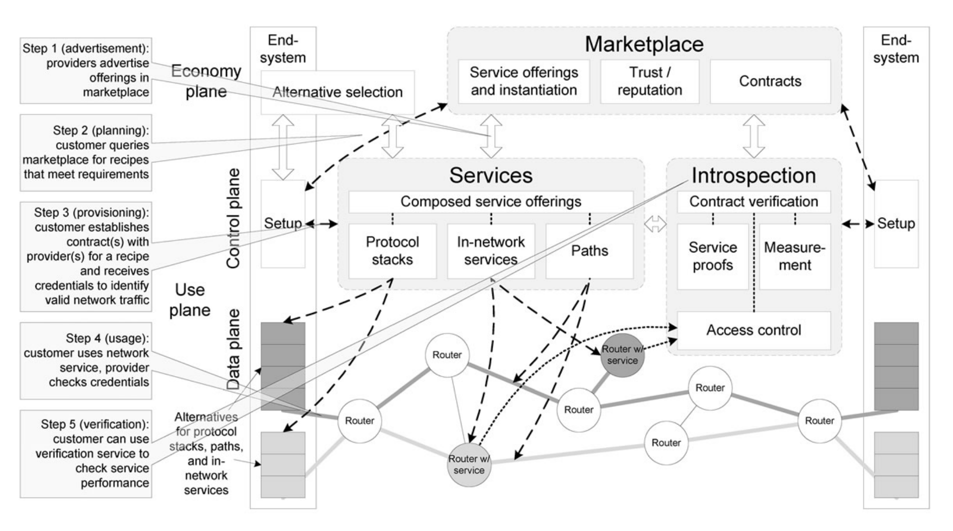


Entities in ChoiceNet

- **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.

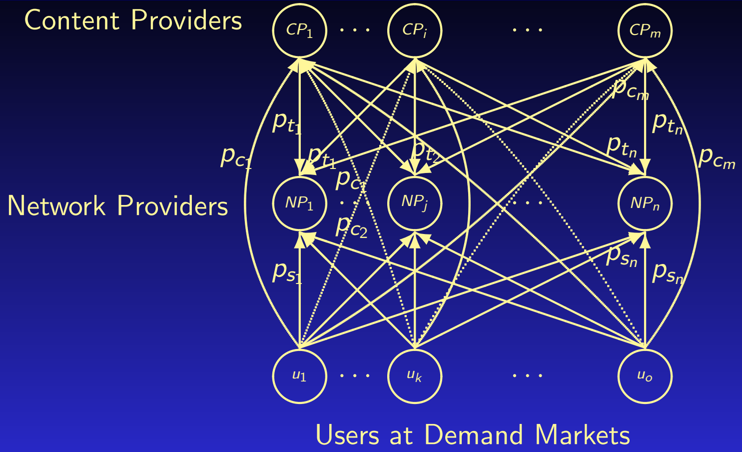
- **Examples**

– 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



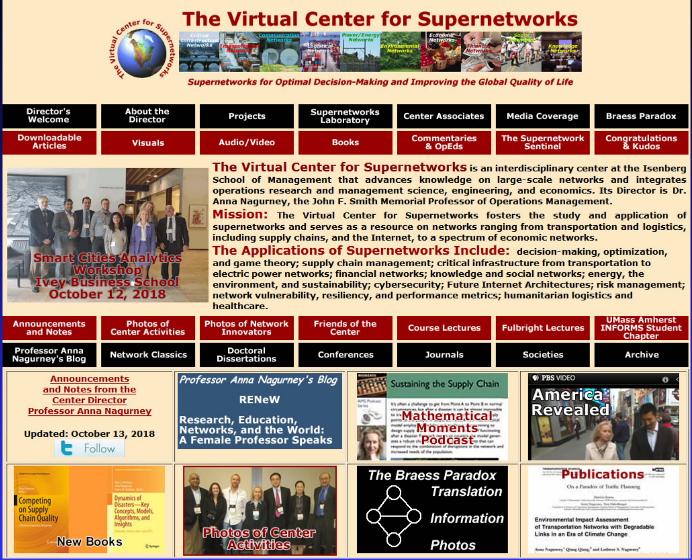
"A Network Economic Game Theory Model of a Service-Oriented Internet with Price and Quality Competition in Both Content and Network Provision," S. Saberi, A. Nagurney, and T. Wolf, *Service Science* **6(4)** (2014), pp 229-250.

INFORMS

The wonderful OR network with strong linkages to its rich past continues to grow and evolve.

It connects us across generations (past, present, and future) and creates linkages to other disciplines.

THANK YOU!



The Virtual Center for Supernetworks

The Virtual Center for Supernetworks

Critical Infrastructure Networks · Transportation Networks · Communication Networks · Logistical Networks · Power/Energy Networks · Environmental Networks · Economic Networks · Financial Networks · Social Networks · Knowledge Networks

Supernetworks for Optimal Decision-Making and Improving the Global Quality of Life

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Downloadable Articles | Visuals | Audio/Video | Books | Commentaries & OpEds | The Supernetwork Sentinel | Congratulations & Kudos

Smart Cities Analytics Workshop Ivey Business School October 12, 2018

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.

Mission: The Virtual Center for Supernetworks fosters the study and application of supernetworks and serves as a resource on networks ranging from transportation and logistics, including supply chains, and the Internet, to a spectrum of economic networks.

The Applications of Supernetworks Include: decision-making, optimization, and game theory; supply chain management; critical infrastructure from transportation to electric power networks; financial networks; knowledge and social networks; energy, the environment, and sustainability; cybersecurity; Future Internet Architectures; risk management; network vulnerability, resiliency, and performance metrics; humanitarian logistics and healthcare.

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Announcements and Notes from the Center Director Professor Anna Nagurney

Updated: October 13, 2018

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Environmental Impact Assessment of Transportation Networks with Degradable Links in an Era of Climate Change