NETWORKS
The Science That Spans Disciplines

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The Virtual Center for Supernetworks
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Outline of Presentation:

- Background
- Examples of Physical Networks
- Network Components
- Scientific Study of Networks
- Classical Networks and Applications
- Interdisciplinary Impact of Networks
- Characteristics of Networks Today
- The Braess Paradox
- Supernetworks
- Novel Applications -- Financial Networks to Social Networks

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Networks are pervasive in our daily lives and essential to the functioning of our societies and economies.

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Everywhere we look:

in business, science,
social systems, technology,
and education,

networks provide the infrastructure for communication, production, and transportation.

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Transportation Networks

provide us with the means to cross distance in order to conduct our work, and to see our colleagues, students, clients, friends, and family members.

They provide us with access to food and consumer products.

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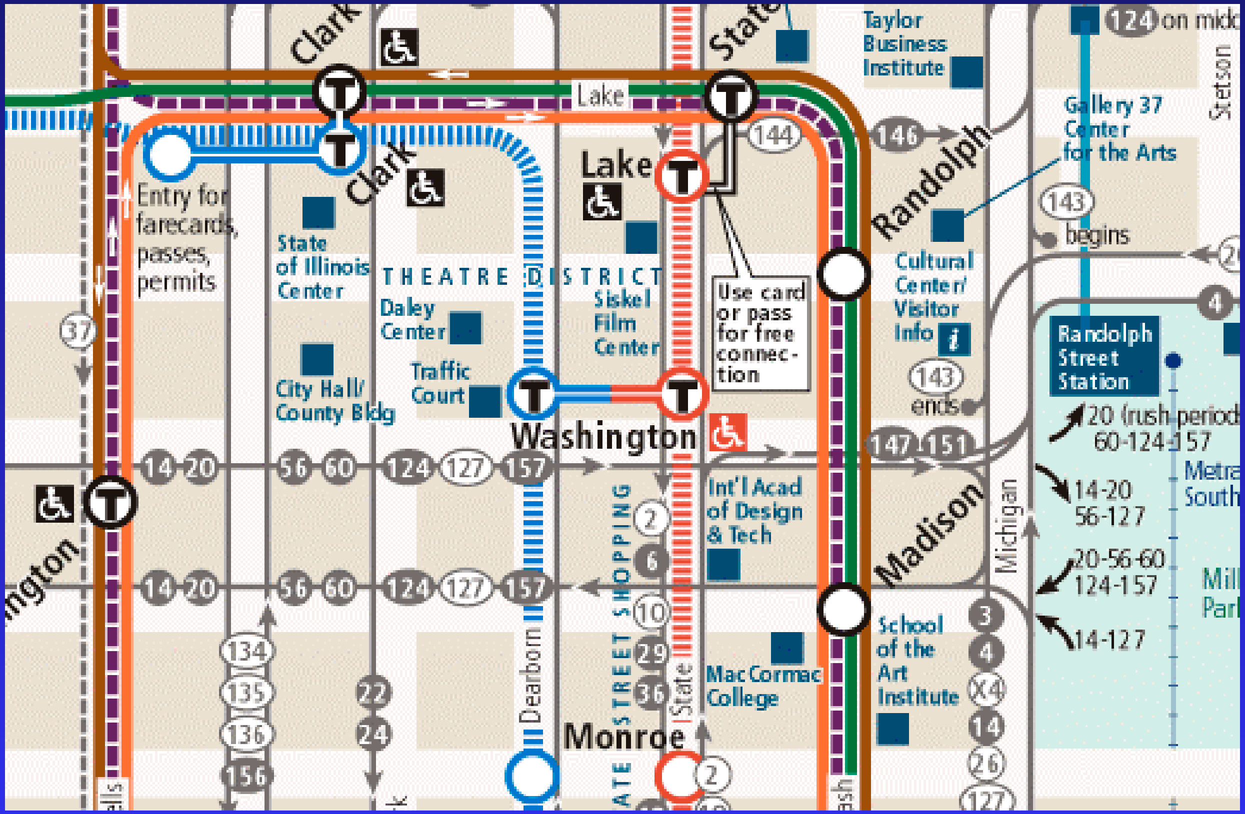
Chicago Transit Authority Route Network



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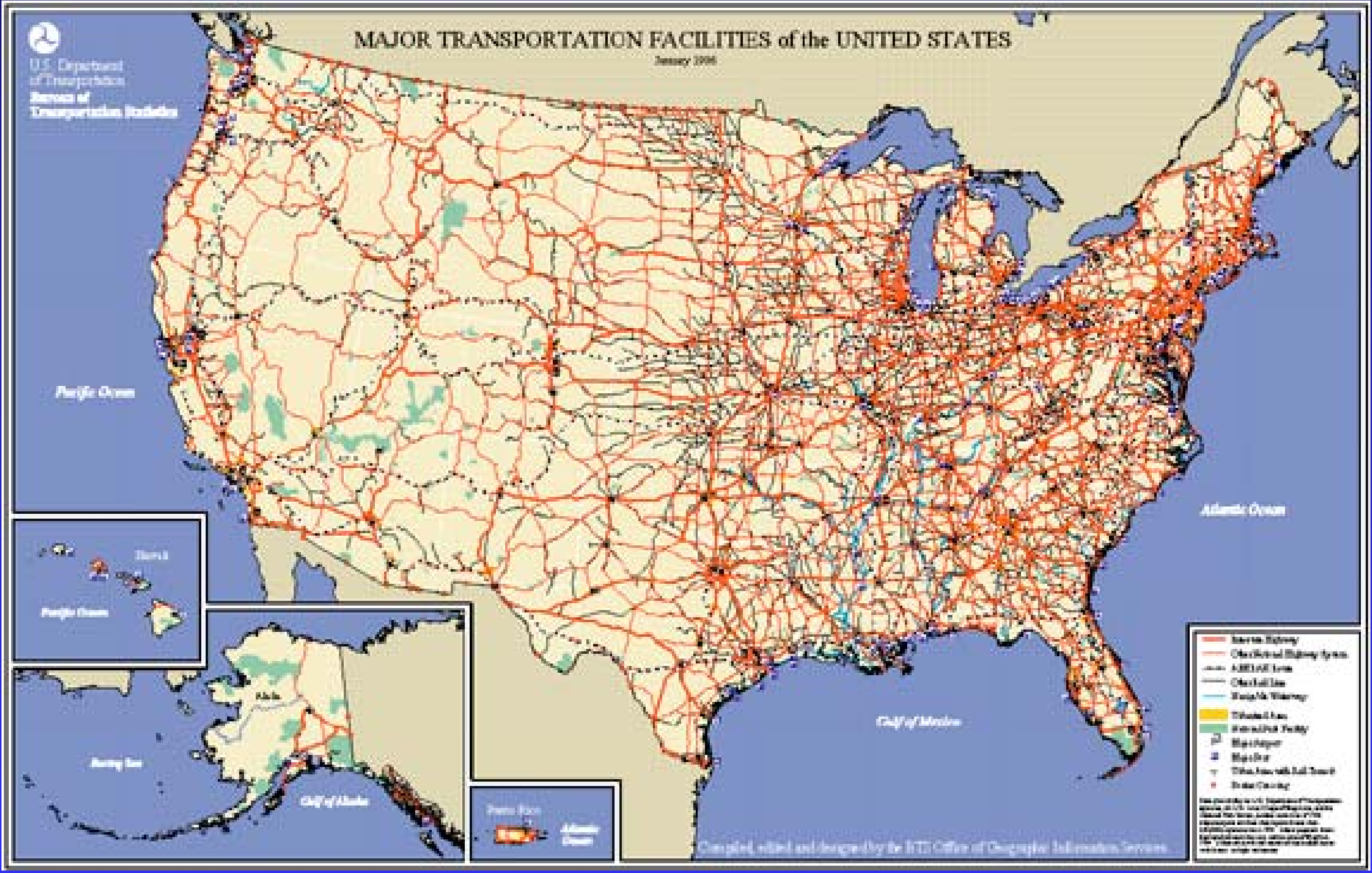
Major Highway and Railroad Networks in the US



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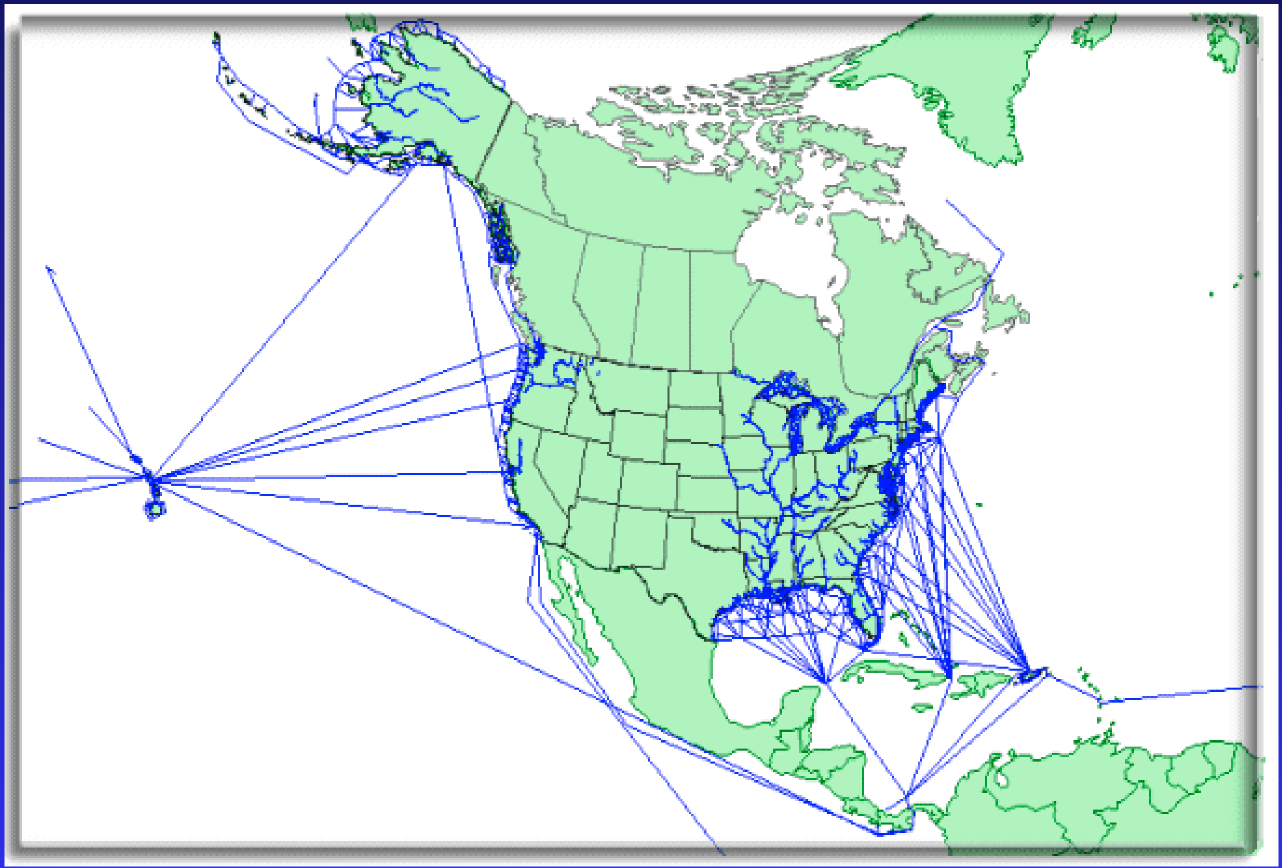
Water Freight Transport Routes for the US



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Communication Networks

- allow us to communicate within our own communities and across regions and national boundaries,
- and have transformed the way we live, work, and conduct business.

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Iridium Satellite Constellation Network

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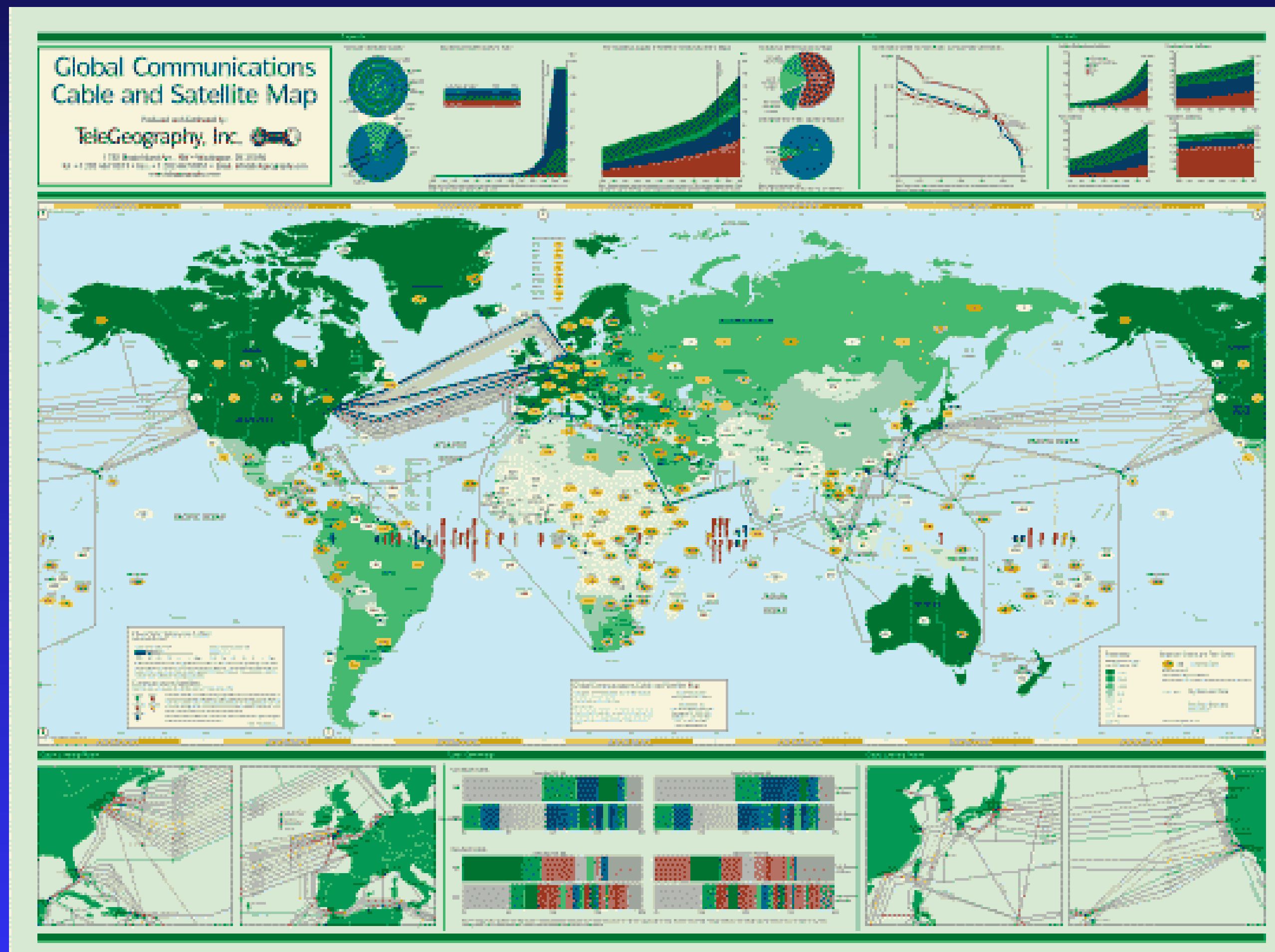
Satellite and Undersea Cable Networks



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Indeed, throughout history, networks have evolved to serve as the foundation for connecting humans to one another and their activities.

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Roads were laid, bridges built, and waterways crossed so that humans, be they on foot, on animal, or vehicle could traverse physical distance through *transportation*. The airways were conquered through flight.

Communications **were conducted using the available means of the period, from smoke signals, drum beats, and pigeons, to the telegraph, telephone, and computer networks of today.**

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The study of the efficient operation on 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.

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Energy Networks

provide the energy for our homes, schools, and businesses, and to run our vehicles.

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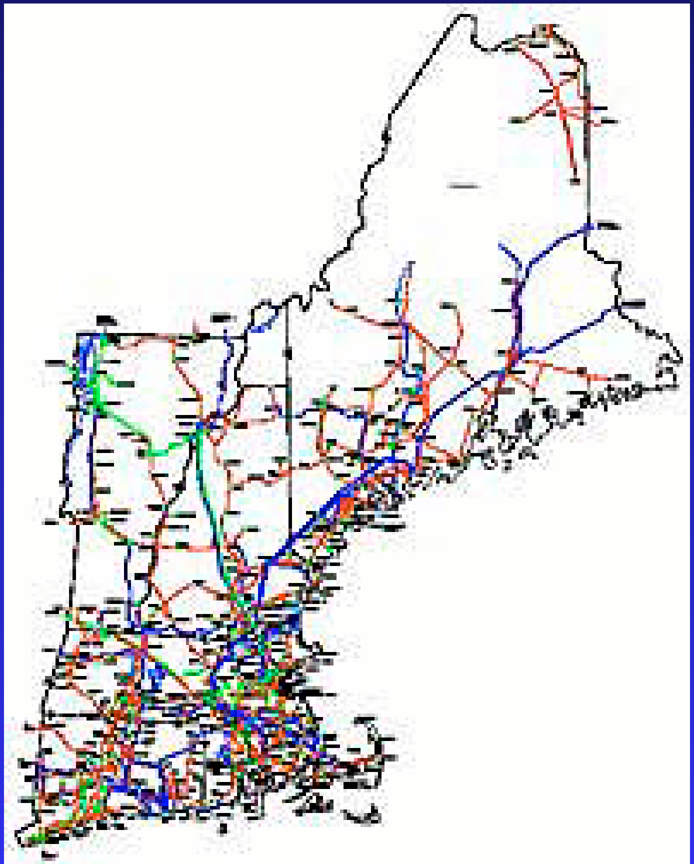
New England Electric Power Network



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Duke Energy Gas Pipeline Network

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The basic components of networks are:

- nodes
- links or arcs
- flows.

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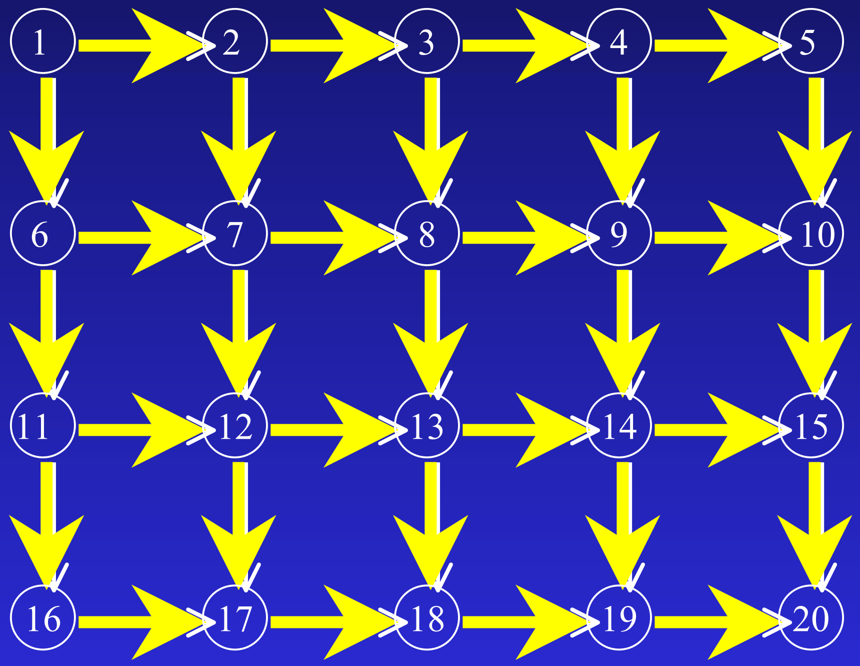
Nodes Links Flows



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Components of Some Common Physical Networks

Network System	Nodes	Links	Flows
Transportation	Intersections, Homes, Workplaces, Airports, Railyards	Roads, Airline Routes, Railroad Track	Automobiles, Trains, and Planes,
Manufacturing and logistics	Workstations, Distribution Points	Processing, Shipment	Components, Finished Goods
Communication	Computers, Satellites, Telephone Exchanges	Fiber Optic Cables Radio Links	Voice, Data, Video
Energy	Pumping Stations, Plants	Pipelines, Transmission Lines	Water, Gas, Oil

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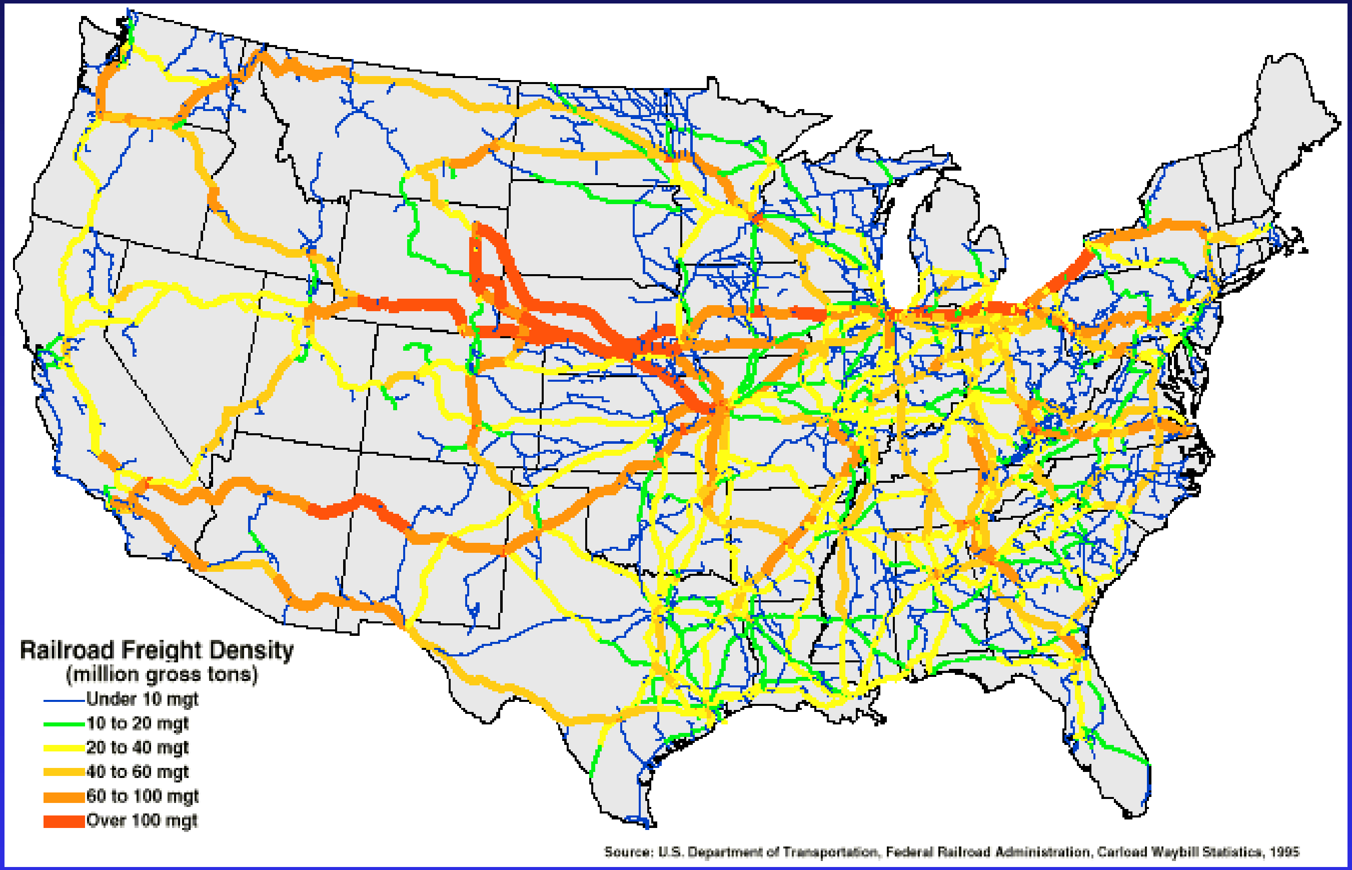
US Railroad Freight Flows



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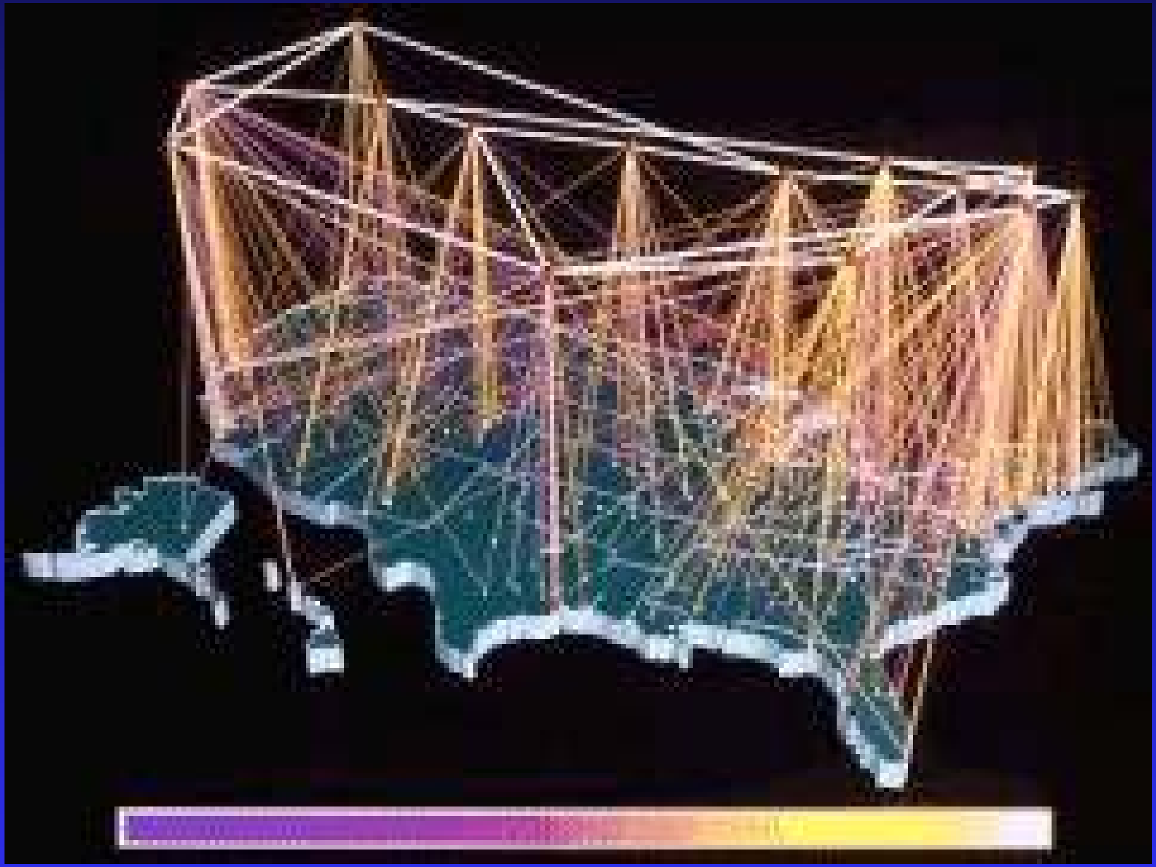
Traffic Flow on NSFNET T1 Backbone Network



from Donna Cox and Robert Patterson, NCSA, 1992

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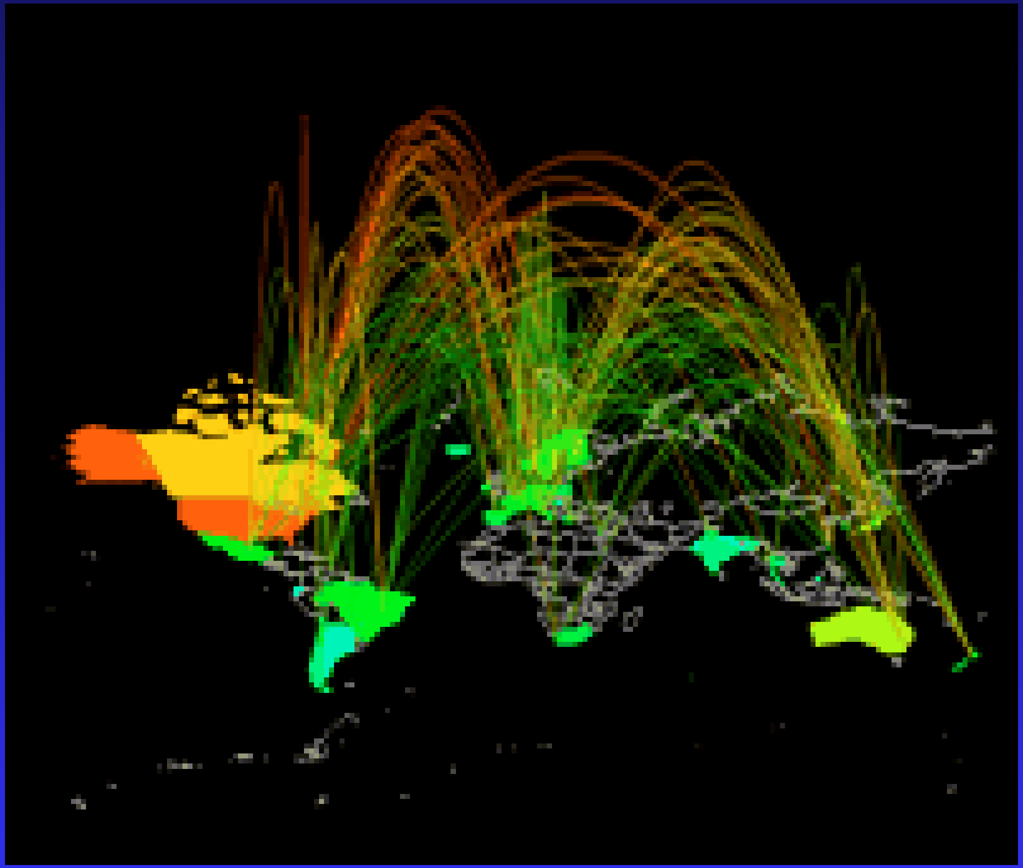
IP Traffic Flows Over One 2 Hour Period



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In a basic network problem domain:

one wishes to move the flow from one node to another in a way that is as efficient as possible.

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The study of networks involves:

- how to **model** such applications - as **mathematical entities,**
- how to **study the models** qualitatively,
- and how to design **algorithms** to solve the resulting models.

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Classic Examples of Network Problems Are:

- The Shortest Path Problem
- The Maximum Flow Problem
- The Minimum Cost Flow Problem.

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Applications of the Shortest Path Problem

Arise in **transportation** and **telecommunications.**

Other applications include:

- simple building evacuation models
- DNA sequence alignment
- dynamic lot-sizing with backorders
- assembly line balancing
- compact book storage in libraries.

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Applications of the Maximum Flow Problem

- machine scheduling
- network reliability testing
- building evacuation.

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Applications of the Minimum Cost Flow Problem

- warehousing and distribution
- vehicle fleet planning
- cash management
- automatic chromosome classification
- satellite scheduling.

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Network problems also arise in other ***surprising and fascinating*** ways for problems, which at first glance and on the surface, may not appear to involve networks at all. Hence, ***the study of networks is not limited to only physical networks*** but also to *abstract* networks in which nodes do not coincide to locations in space.

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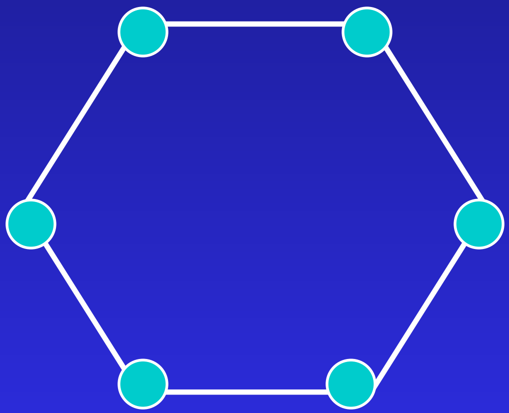
In fact, Quesnay in 1758 in his *Tableau Economique* introduced an abstract network in the form of a graph to depict the circular flow of financial funds in an economy.



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The advantages of a scientific network formalism:

- many present-day problems are concerned with flows (material, human, capital, informational, etc.) over space and time and, hence, ideally suited as an application domain for network theory;
- provides a graphical or visual depiction of different problems;

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- **helps to identify similarities and differences in distinct problems through their underlying network structure;**
- **enables the application of efficient network algorithms;**
- **allows for the study of disparate problems through a unifying methodology.**

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- One of the primary purposes of scholarly and scientific investigation is to ***structure*** the world around us and to ***discover patterns*** that cut across boundaries and, hence, help to ***unify diverse applications***.
- Network theory provides us with a ***powerful methodology*** to establish connections with different disciplines and to ***break down boundaries***.

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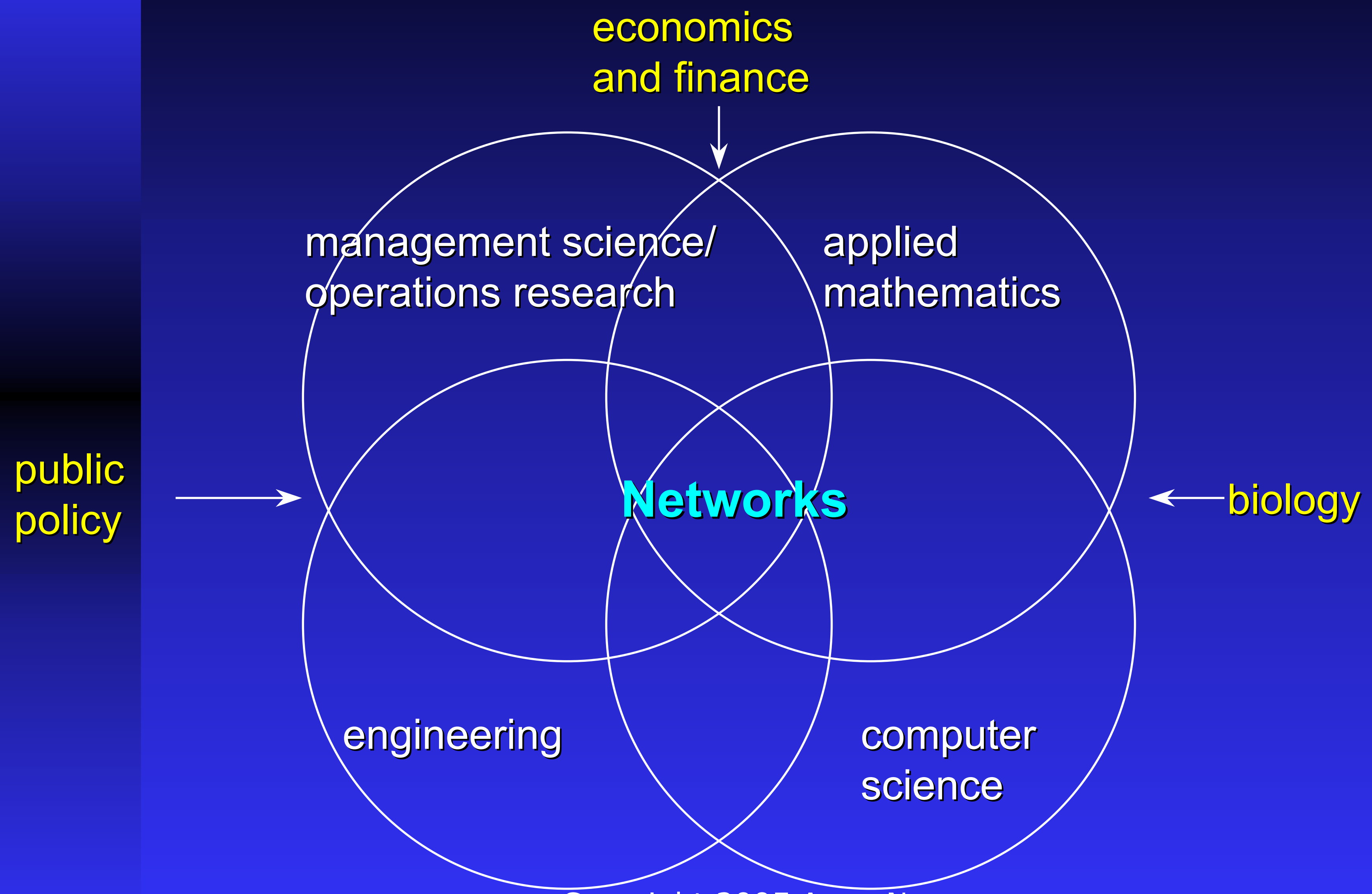

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Interdisciplinary Impact of Networks

Finance and Economics

Interregional Trade

General Equilibrium

Industrial Organization

Portfolio Optimization

Flow of Funds Accounting

Engineering

Energy

Manufacturing

Telecommunications

Transportation

Networks

Sociology

Social Networks

Organizational Theory

Computer Science

Routing Algorithms

Biology

DNA Sequencing

Targeted Cancer Therapy

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Characteristics of Networks Today

- ***large-scale nature*** **and complexity of network topology;**
- ***congestion*****;**
- **alternative behavior of users of the network, which may lead to** ***paradoxical phenomena*****;**
- **the** ***interactions among networks*** **themselves such as in transportation versus telecommunications networks;**
- ***policies*** **surrounding networks today may have a** ***major impact*** **not only economically but also** ***socially, politically, and security-wise*****.**

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- **large-scale nature and complexity of network topology**
  - In **Chicago's Regional Network**, there are 12,982 nodes, 39,018 links, and 2,297,945 O/D pairs.
  - **AT&T's domestic network** has 100,000 O/D pairs. In their call detail graph applications (nodes are phone numbers, edges are calls) - 300 million nodes and 4 billion edges

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- **congestion is playing an increasing role in transportation networks:**

  For example in the United States alone, congestion results in $100 billion in lost productivity annually, whereas the figure in Europe is estimated to be $150 billion.

  The number of cars is expected to increase by 50% by 2010 and to double by 2030.

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Congestion

Courtesy: Pioneer Valley Planning Commission

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Wasting Away in Traffic

	Annual delay hours/driver
Los Angeles	93
San Francisco - Oakland	73
Washington, DC	67
Dallas	61
Atlanta	60
Houston	58
Chicago	56
Boston	54
Detroit	53
Miami - Hialeah	52

Source: Texas Transportation Institute 2002 Data

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- **alternative behaviors of the users of the network**
  - **system-optimized versus**
  - **user-optimized, which may lead to**

paradoxical phenomena.

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System-Optimization versus User-Optimization

In transportation networks, travelers select their routes of travel from an origin to a destination so as to minimize their own travel cost or travel time, which although *optimal* from an individual's perspective (*user-optimization*) may not be optimal from a societal one (*system-optimization*) where one has control over the flows on the network.

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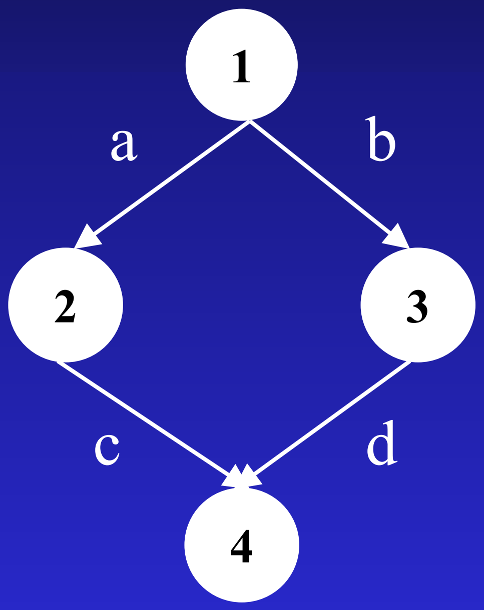
The Braess' Paradox

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

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



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

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

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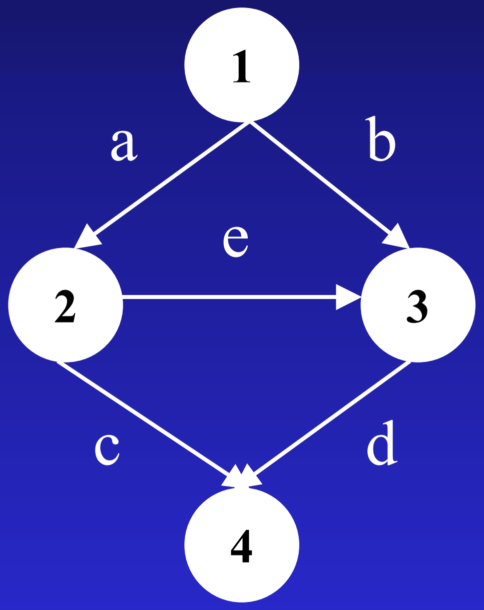
Adding a Link Increased Travel Cost for All!

- 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 costs: $C_{p_1} = C_{p_2} = C_{p_3} = 92$.



$c_e(f_e) = f_e + 10$

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This phenomenon is also relevant to telecommunications networks and, in particular, to the Internet which is another example of a noncooperative network.

The Price of Anarchy!!!

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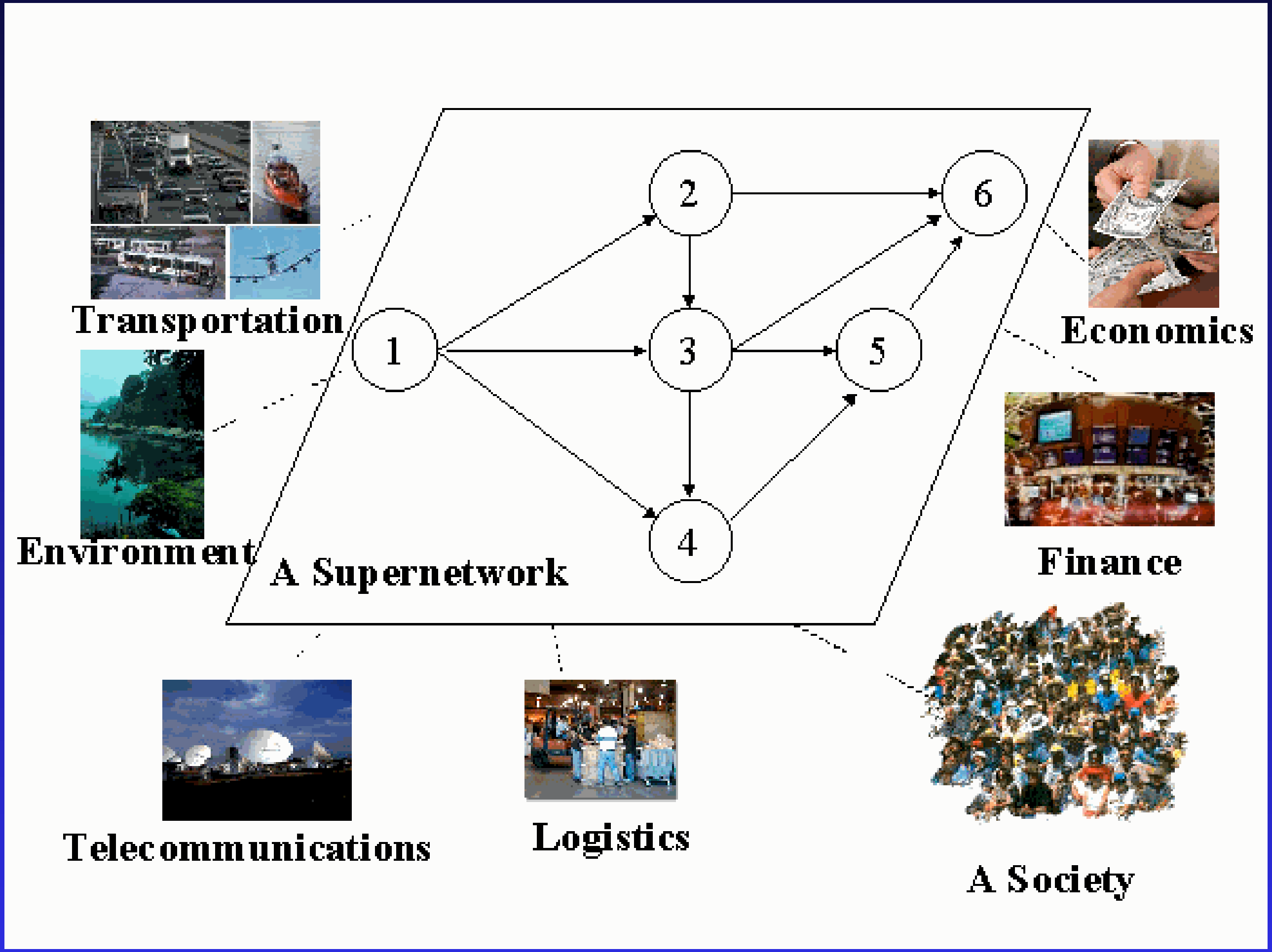
A New Paradigm

Supernetworks: A New Paradigm



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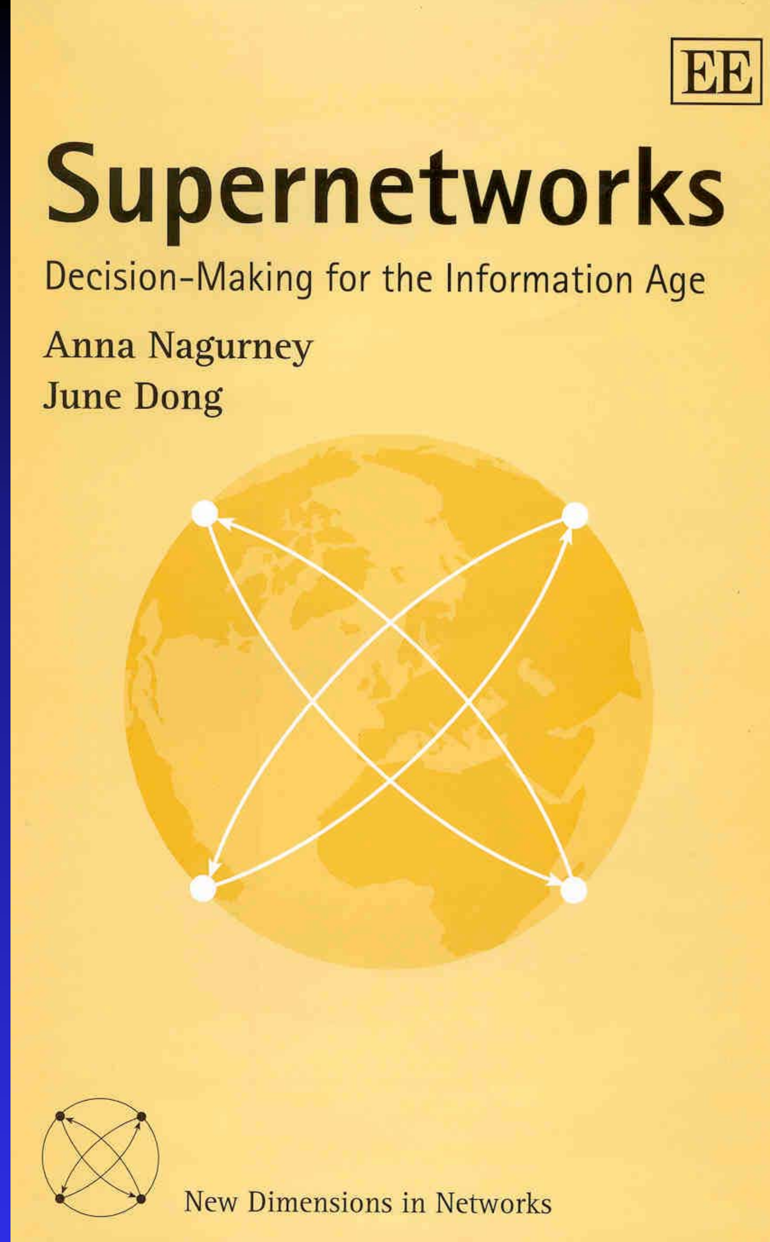

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Supernetworks

- Supernetworks may be comprised of such networks as transportation, telecommunication, logistical, and/or financial networks.

- They may be *multilevel* as when they formalize the study of supply chain networks or *multitiered* as in the case of financial networks with intermediation.

- Decision-makers may be faced with multiple criteria; thus, the study of supernetworks also includes the study of *multicriteria decision-making*.

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New Tools

The tools that we have been using in our supernetworks research include:

- network theory
- optimization theory
- game theory
- variational inequality theory and
- projected dynamical systems theory (which we have been instrumental in developing)
- network visualization tools.

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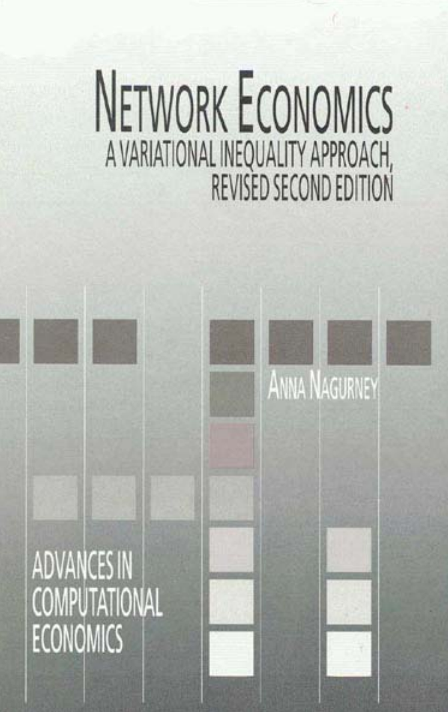
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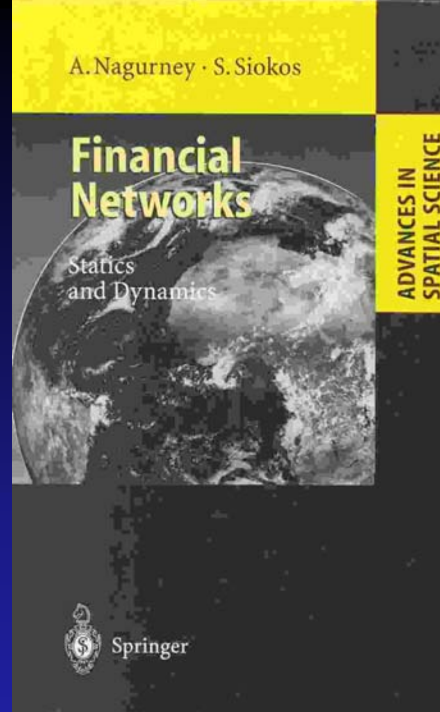
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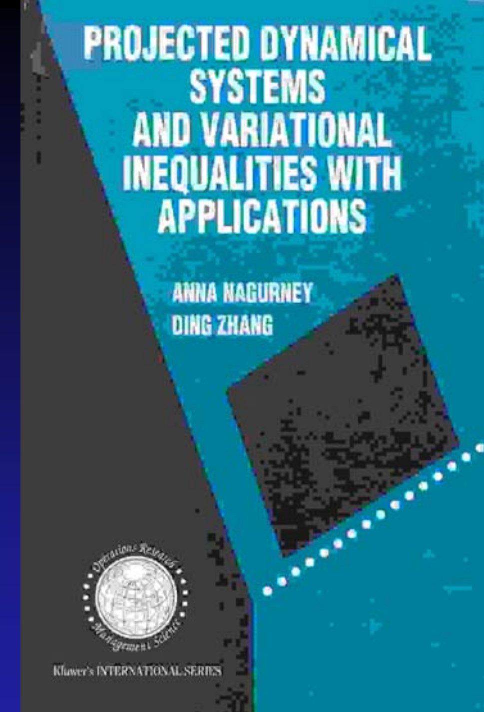
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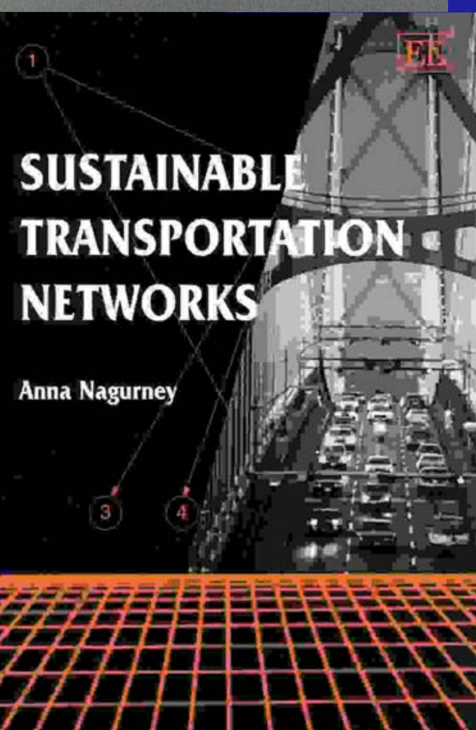
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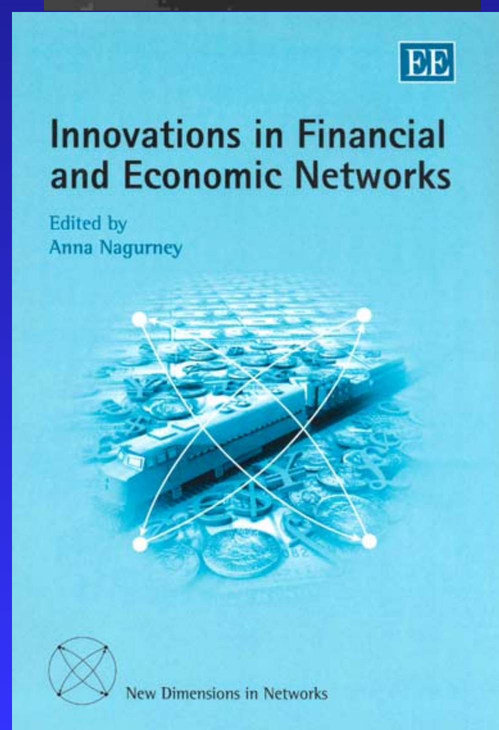
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New Dimensions in Networks

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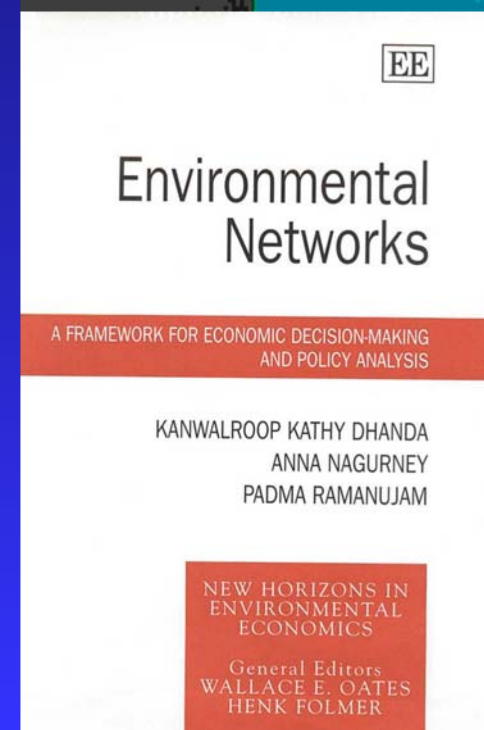
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General Editors
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We are interested not only in addressing topological issues in terms of connectivity but in predicting the various flows on the networks whether physical or abstract subject to human decision-making under the associated constraints, be they budget, time, security, risk, and/or cost-related.

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Novel Applications

Applications of Supernetworks

- Telecommuting/Commuting Decision-Making
- Teleshopping/Shopping Decision-Making
- Supply Chain Networks with Electronic Commerce
- Financial Networks with Electronic Transactions
- Reverse Supply Chains with E-Cycling
- Knowledge Networks
- Energy Networks/Power Grids

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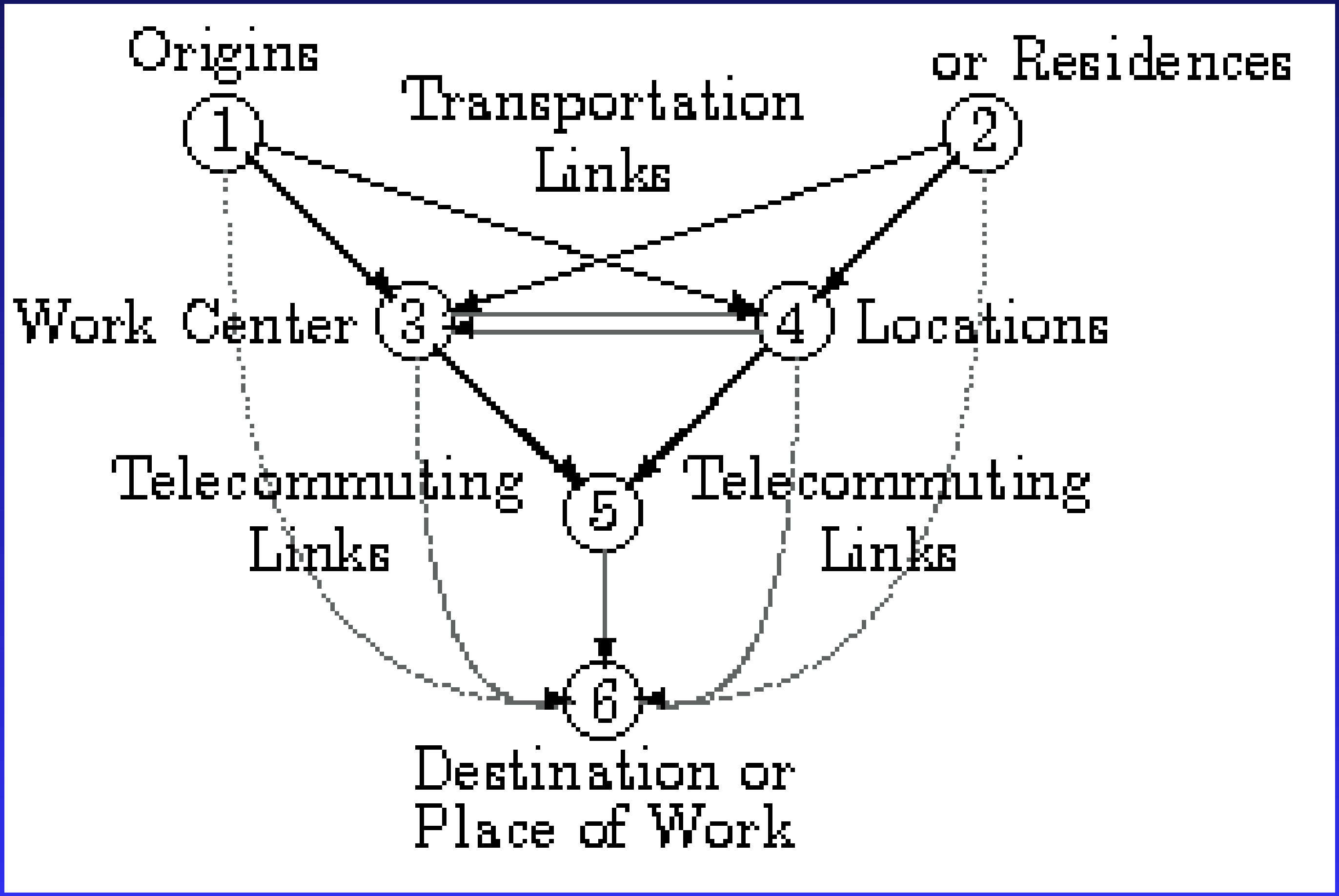
A Supernetwork Conceptualization of Commuting versus Telecommuting



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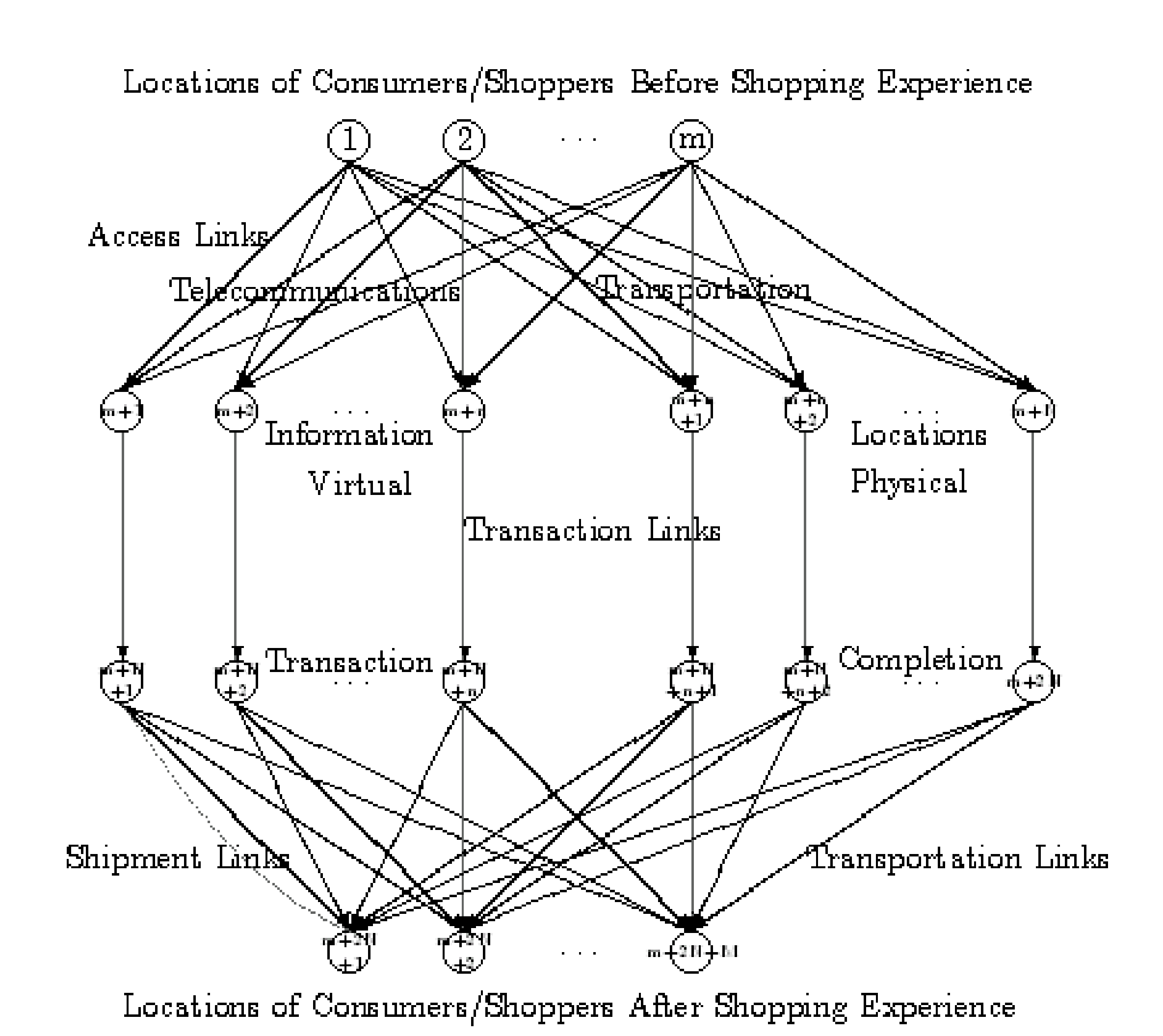
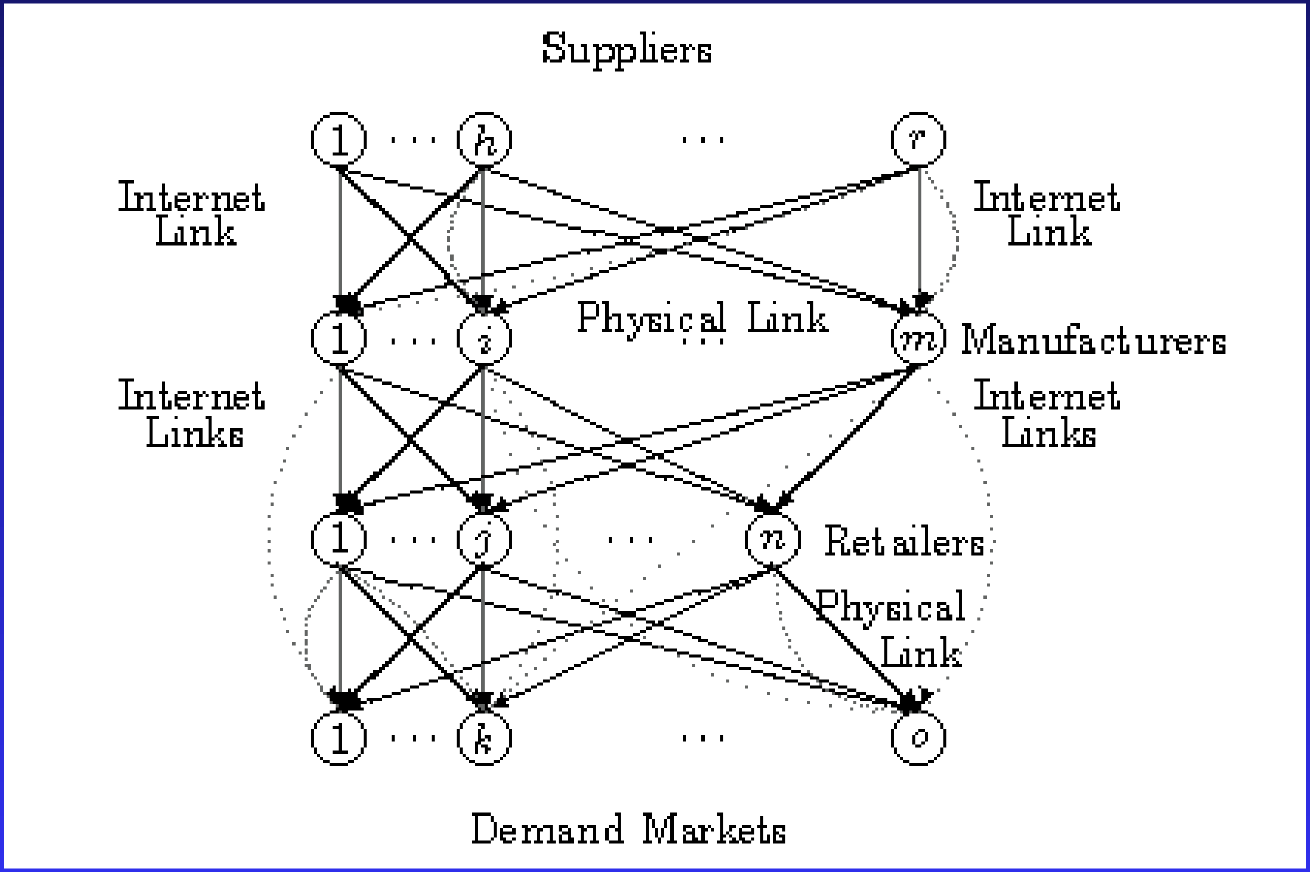
A Supernetwork Framework for Teleshopping versus Shopping



The Supernetwork Structure of a Supply Chain Network



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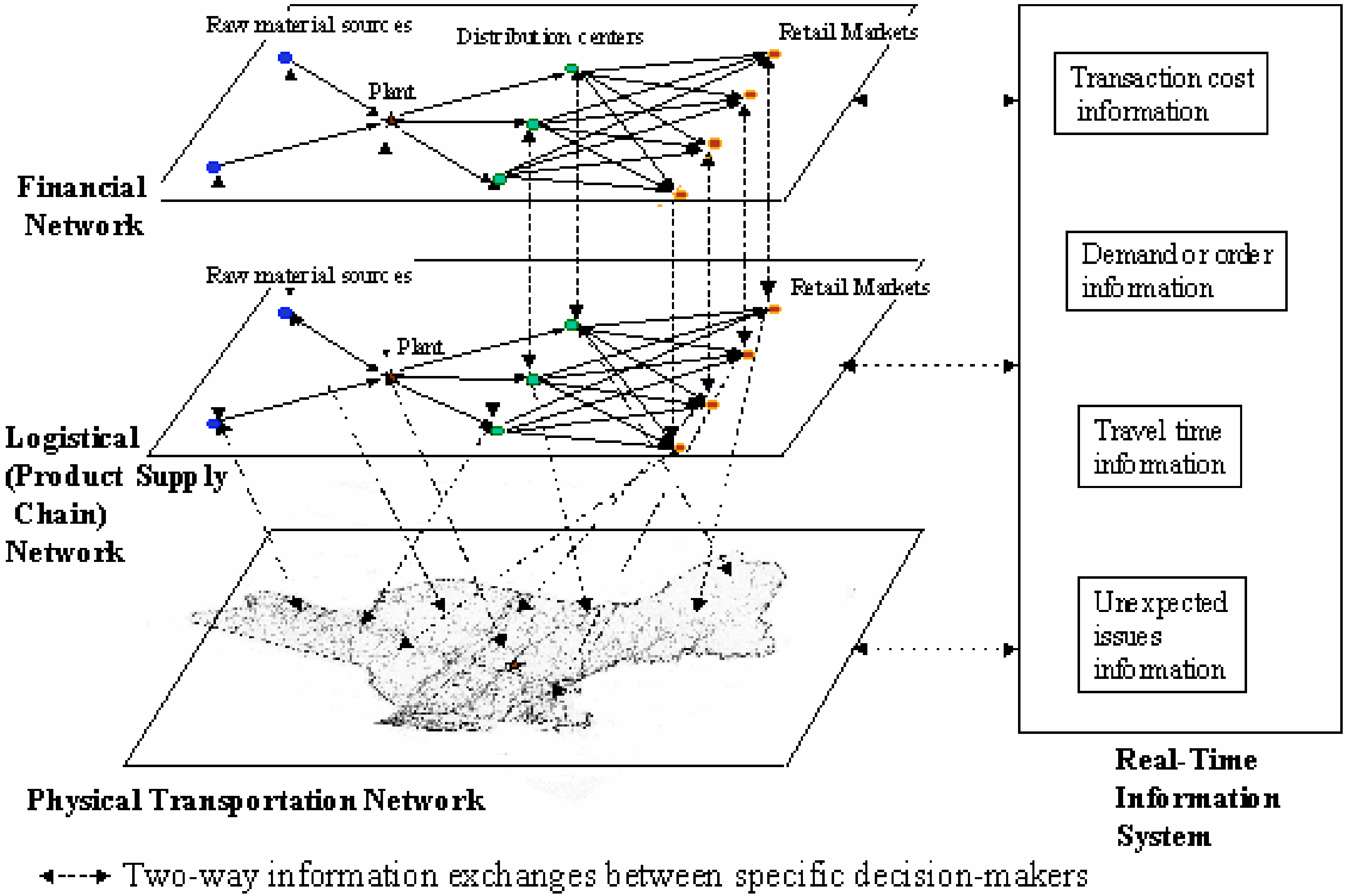
Supply Chain -Transportation Supernetwork Representation



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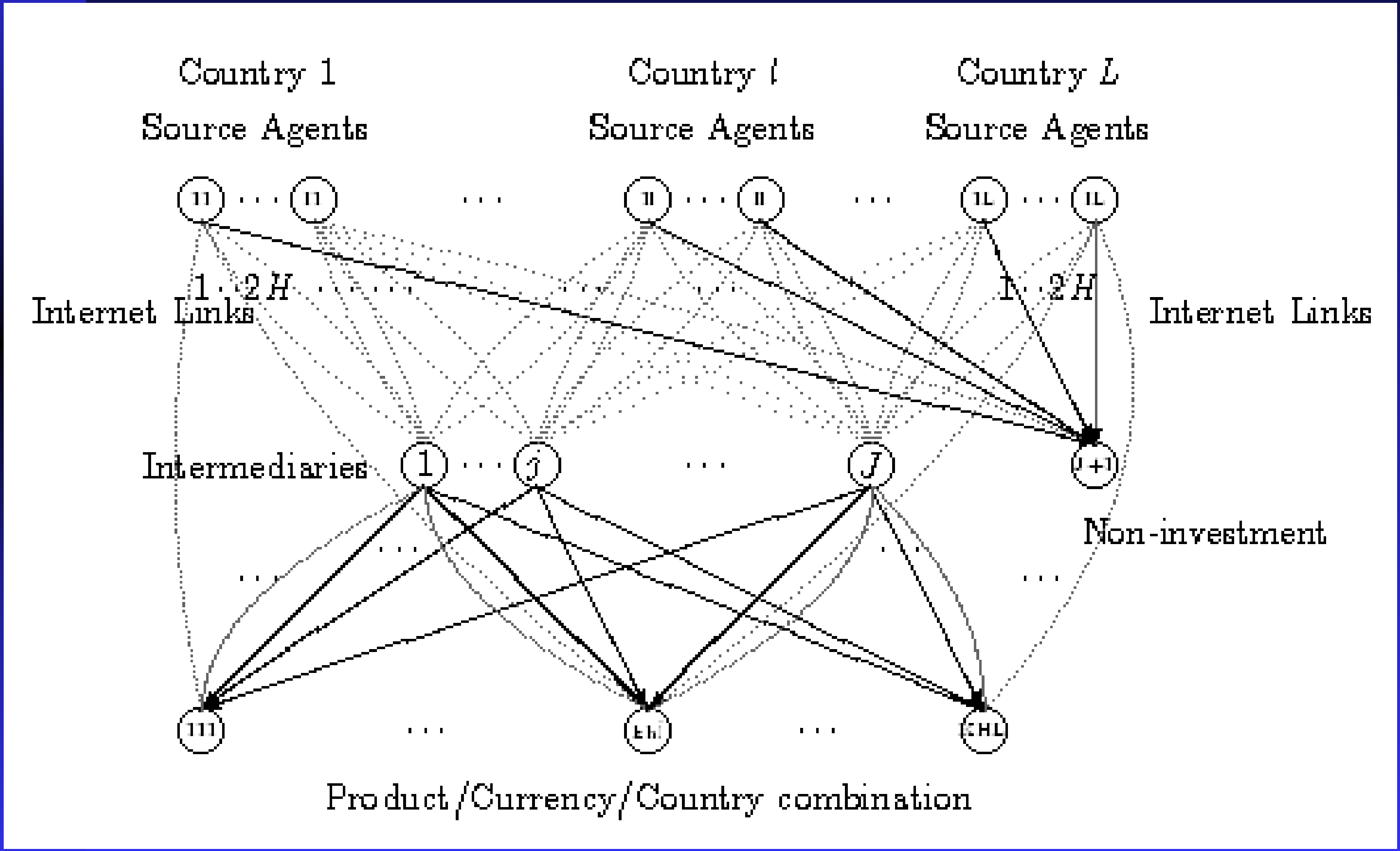
International Financial Networks with Electronic Transactions



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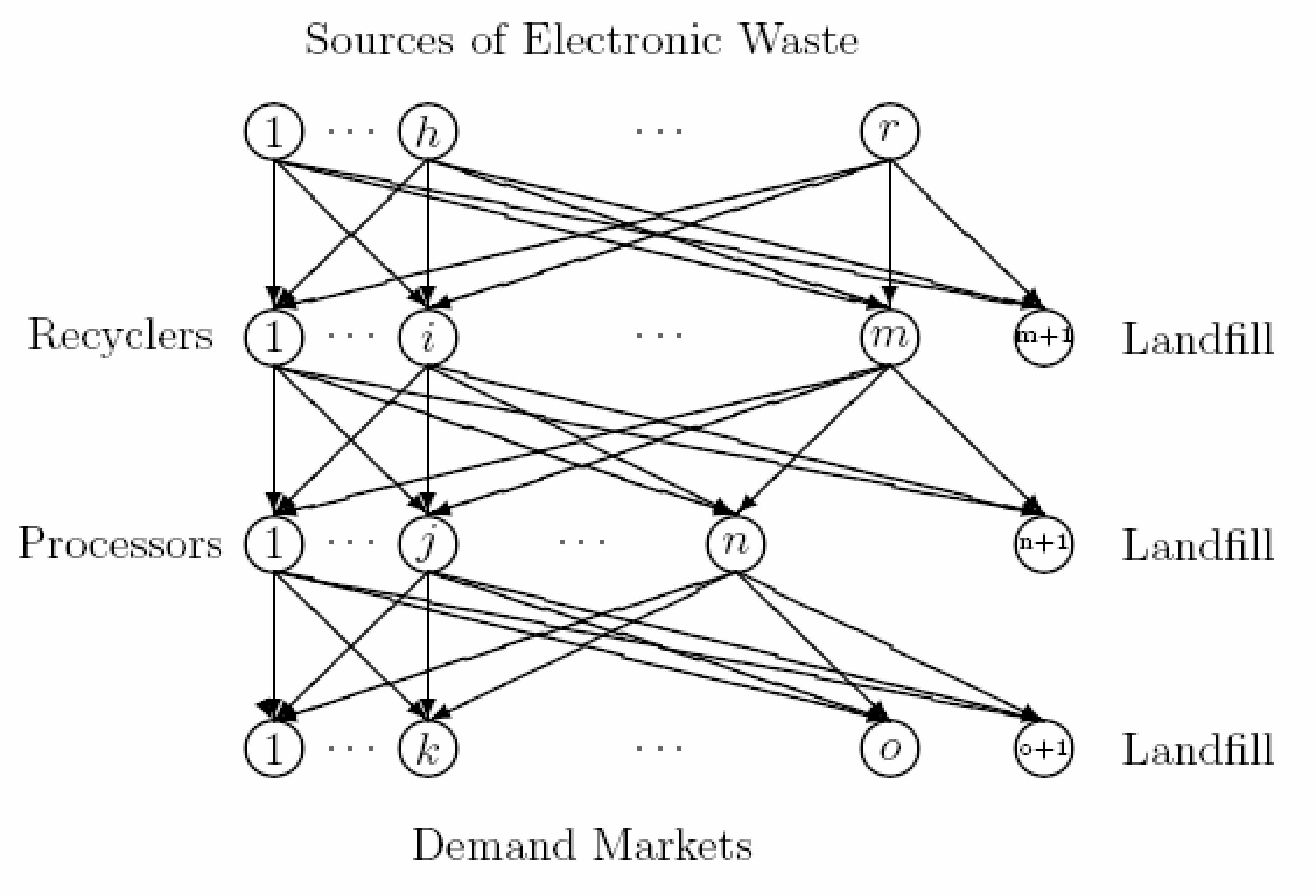
The 4-Tiered E-Cycling Network



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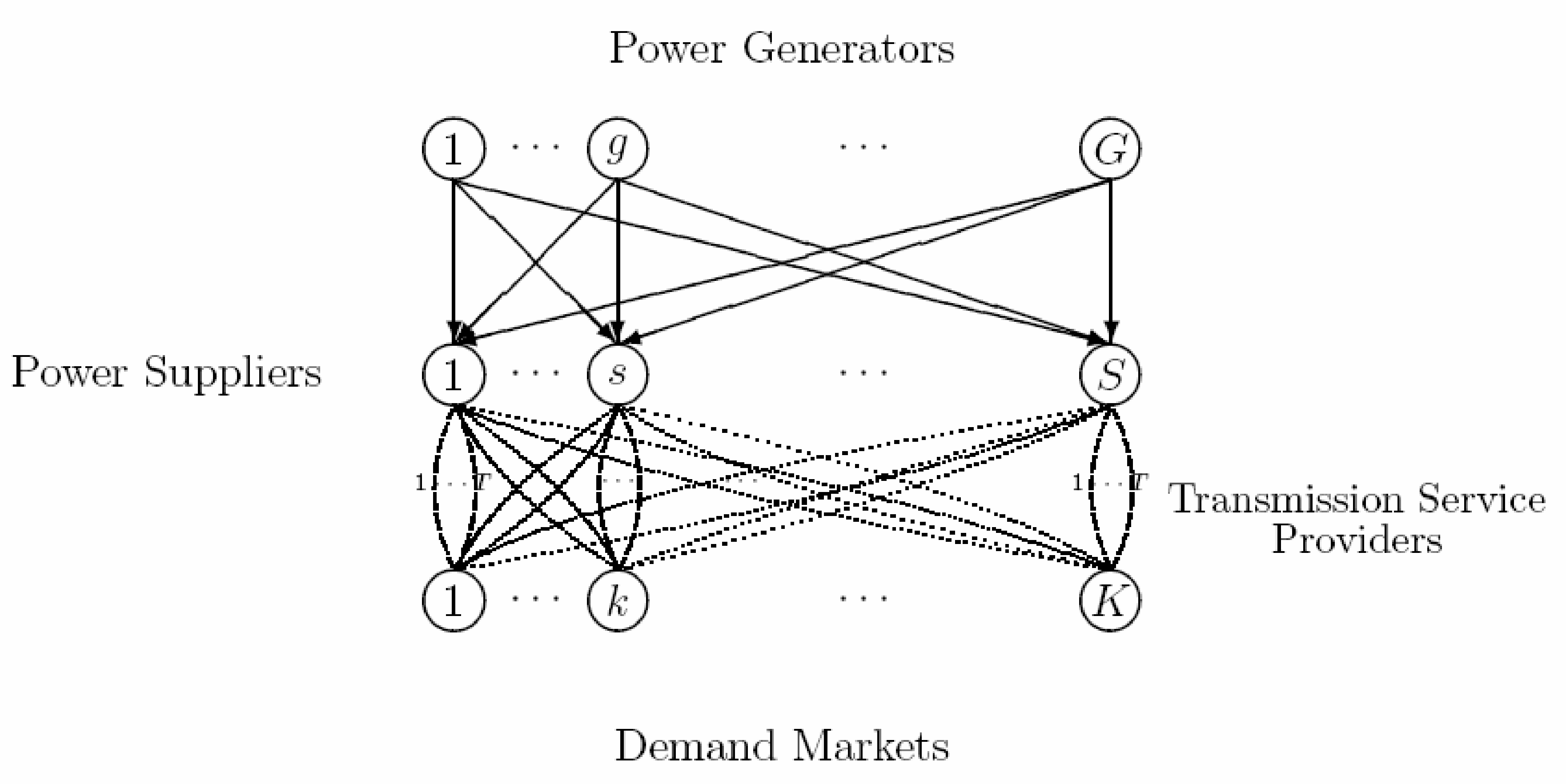
The Electric Power Supply Chain Network



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Supernetworks Integrating Social Networks

The models explicitly consider the role that relationship levels play in other network systems and include multicriteria decision-making with individual weights for the criteria such as:

- maximization of profit
- minimization of risk
- maximization of relationship value.

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Supernetworks Integrating Social Networks

Decision-makers in the network can decide about the relationship levels [0,1] that they want to establish.

Establishing relationship levels incurs some costs.

Higher relationship levels

- Reduce transaction costs
- Reduce risk
- Have some additional value (relationship value).

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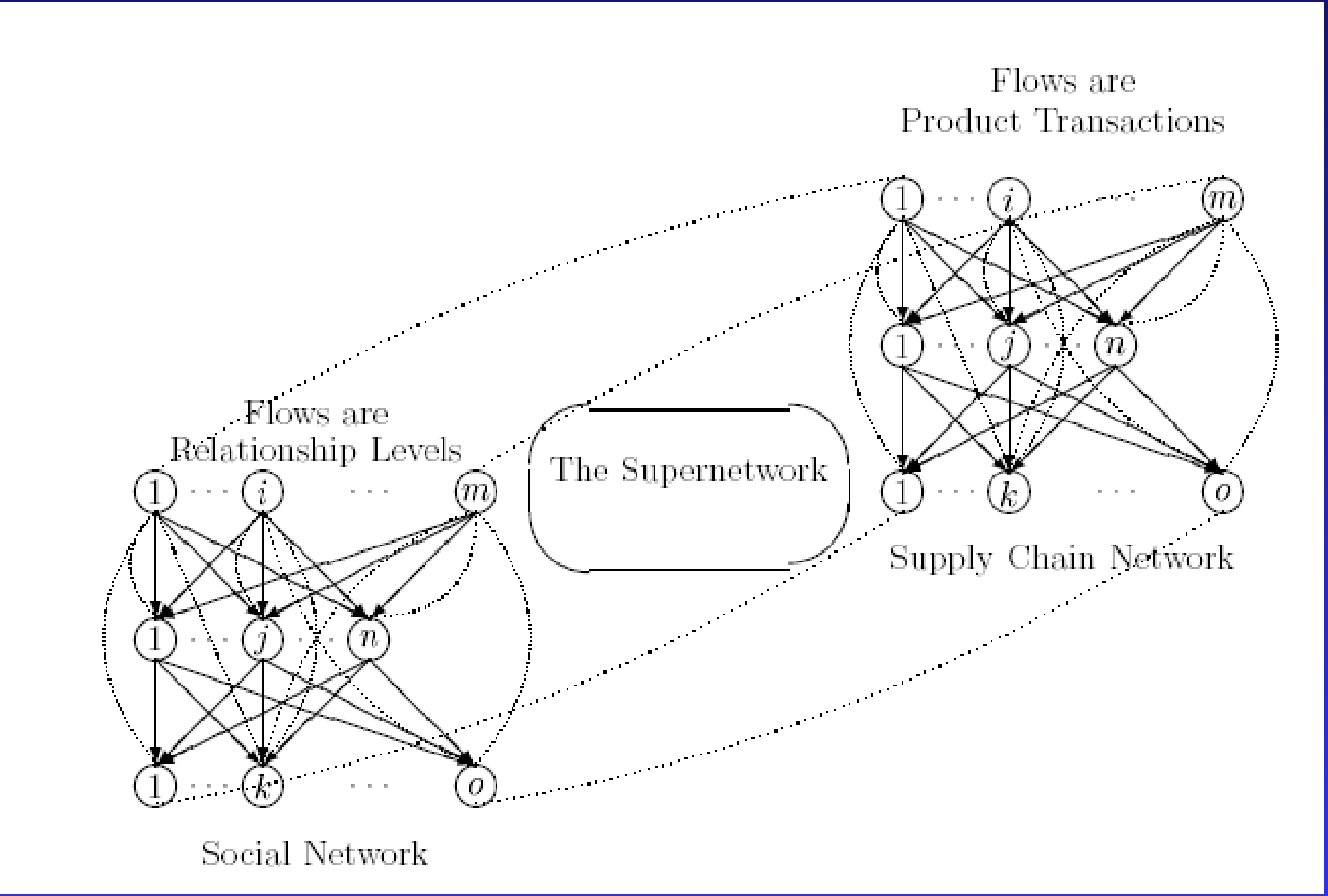
Supernetwork Structure: Integrated Supply Chain/Social Network System



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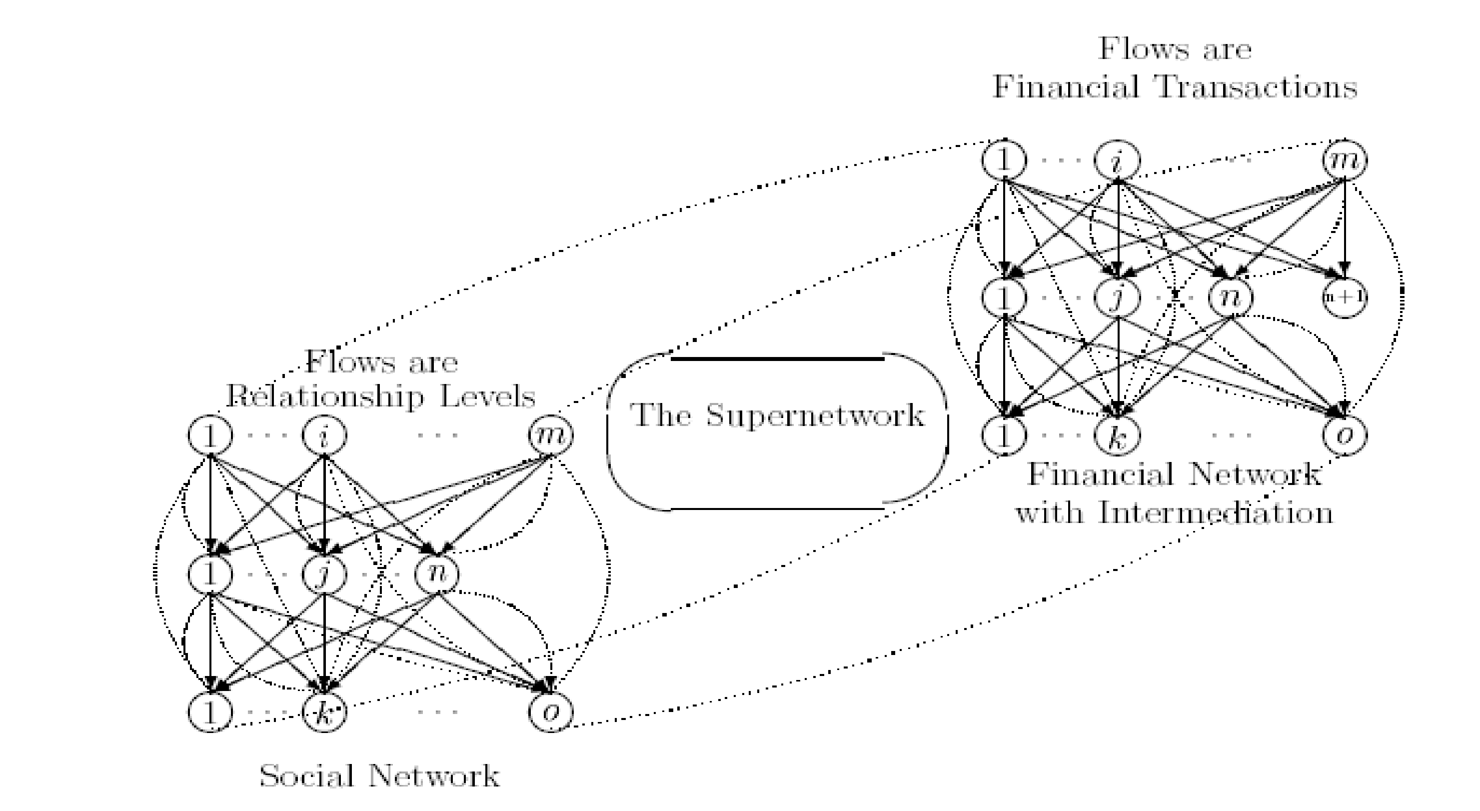
Supernetwork Structure: Integrated Financial/Social Network System



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Supernetworks Integrating Social Networks

Dynamic evolution of:

- Product transactions/financial flows and associated prices on the supply chain network/financial network with intermediation

- Relationship levels on the social network

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Summary and Conclusions

- We have seen the pervasiveness of networks and have pointed out some of the tools used for the study of networks today.

- We have also emphasized the reality of today's networks from congestion to interactions among networks and different behaviors of those using networks.

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- **Finally, we have illustrated through a wide spectrum of applications how networks span disciplines.**

- **The topic and importance of networks to our economies and societies is bringing different communities together from scientists to practitioners in order to further advance the science of networks and its fascinating applications.**

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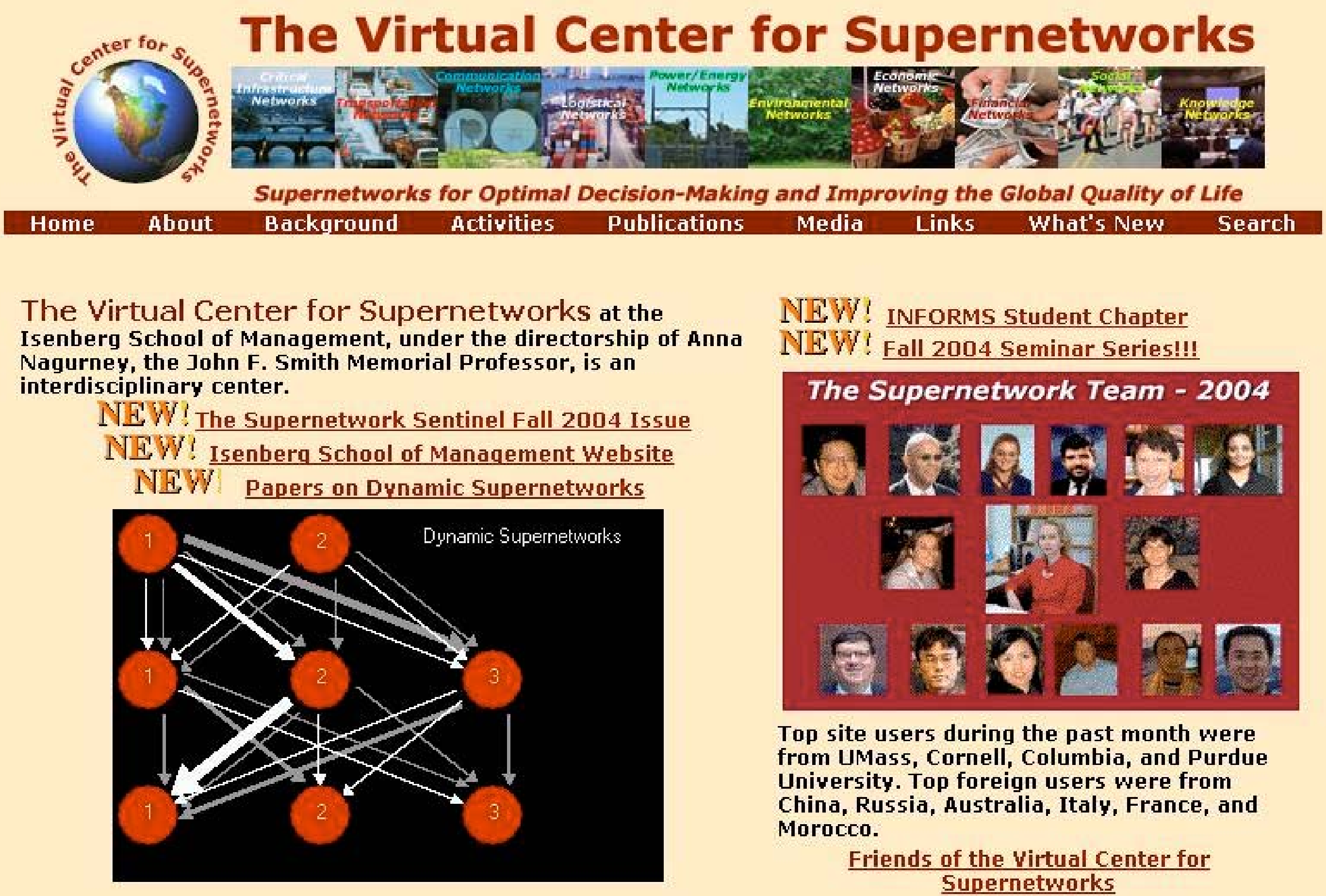
Additional Material and Information can be found at the Virtual Center for Supernetworks site: http://supernet.som.umass.edu



Thank you!

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