Supernetworks: The Why, The How, and Applications

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Network problems also arise in 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.
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.
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;
- 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**.
Interdisciplinary Impact of Networks

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

Engineering
- Energy
- Manufacturing
- Telecommunications
- Transportation

Biology
- DNA Sequencing
- Targeted Cancer Therapy

Sociology
- Social Networks
- Organizational Theory

Computer Science
- Routing Algorithms
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*. 
- **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
congestion is playing an increasing role in transportation networks:

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

The number of cars is expected to increase by 50\% by 2010 and to double by 2030.
# Wasting Away in Traffic

<table>
<thead>
<tr>
<th>City</th>
<th>Annual delay hours/driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles</td>
<td>93</td>
</tr>
<tr>
<td>San Francisco - Oakland</td>
<td>73</td>
</tr>
<tr>
<td>Washington, DC</td>
<td>67</td>
</tr>
<tr>
<td>Dallas</td>
<td>61</td>
</tr>
<tr>
<td>Atlanta</td>
<td>60</td>
</tr>
<tr>
<td>Houston</td>
<td>58</td>
</tr>
<tr>
<td>Chicago</td>
<td>56</td>
</tr>
<tr>
<td>Boston</td>
<td>54</td>
</tr>
<tr>
<td>Detroit</td>
<td>53</td>
</tr>
<tr>
<td>Miami - Hialeah</td>
<td>52</td>
</tr>
</tbody>
</table>

Source: Texas Transportation Institute 2002 Data
alternative behaviors of the users of the network

- system-optimized versus user-optimized, which may lead to paradoxical phenomena.
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.
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
\quad c_c(f_c) = f_c + 50 \quad c_d(f_d) = 10 \ f_d
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: \( C_{p_1} = C_{p_2} = C_{p_3} = 92 \).

\[ c_e(f_e) = f_e + 10 \]
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!!!
A New Paradigm
Supernetworks: A New Paradigm
Supernetworks
Decision-Making for the Information Age
Anna Nagurney
June Dong

New Dimensions in Networks
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.
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.
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.
The Supernetwork Team
2005 - 2006
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
A Supernetwork Conceptualization of Commuting versus Telecommuting
A Supernetwork Framework for Teleshopping versus Shopping
The Supernetwork Structure of a Supply Chain Network
Supply Chain - Transportation Supernetwork Representation

- Financial Network
- Logistical (Product Supply Chain) Network
- Physical Transportation Network

Two-way information exchanges between specific decision-makers

transaction cost information

Demand or order information

Travel time information

Unexpected issues information

Real-Time Information System
International Financial Networks with Electronic Transactions

Diagram showing connections between countries and intermediaries, with labels for source agents, internet links, intermediaries, product/currency/country combinations, and non-investment.
The 4-Tiered E-Cycling Network
The Electric Power Supply Chain Network

Power Generators

Power Suppliers

Transmission Service Providers

Demand Markets
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.
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).
Supernetwork Structure: Integrated Supply Chain/Social Network System
Supernetwork Structure: Integrated Financial/Social Network System
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
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.
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.
Additional Material and Information can be found at the Virtual Center for Supernetworks site: http://supernet.som.umass.edu