The Era of Supernetworks

Anna Nagurney

John F. Smith Memorial Professor
Director – Virtual Center for Supernetworks
Isenberg School of Management
University of Massachusetts Amherst

Congreso Futuro, 14 al 20 Enero, Chile

We Are in an Era of Supernetworks

Supernetworks are Networks of Networks.

Supernetworks Underpin Our Economies and Societies

Networks allow for the Flow of People, Products, Energy, and Information Across Regions and the Globe.

A Supply Chain is an Example of a Supernetwork

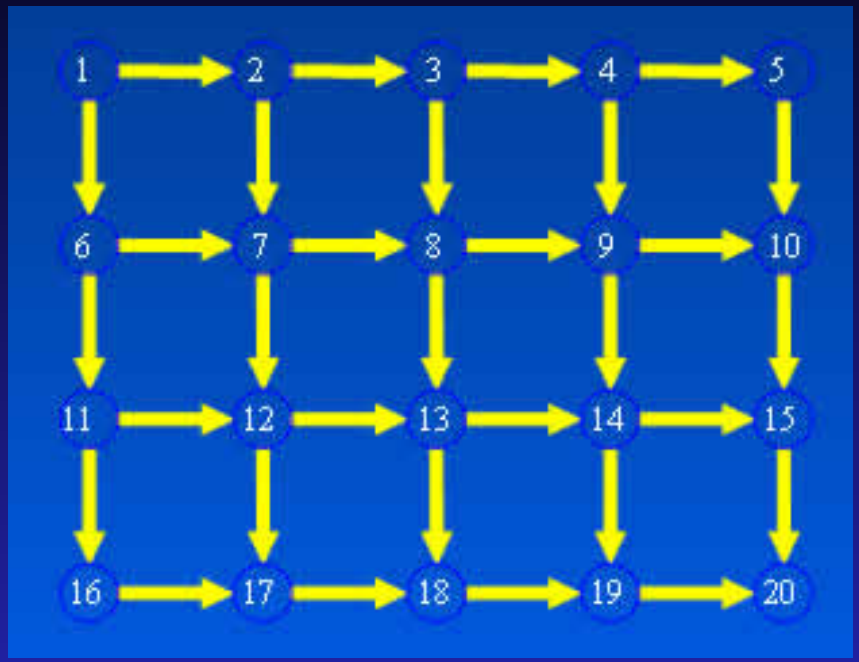
Supply chains have revolutionized the production, storage, and distribution of products and serve as critical infrastructure networks for economic activities.

Examples of Supply Chains

Making Sense of Complexity Through Mathematics

I utilize mathematical and operations research techniques of **optimization**, **game theory**, and **dynamical systems** to gain insights into the behavior of network systems.

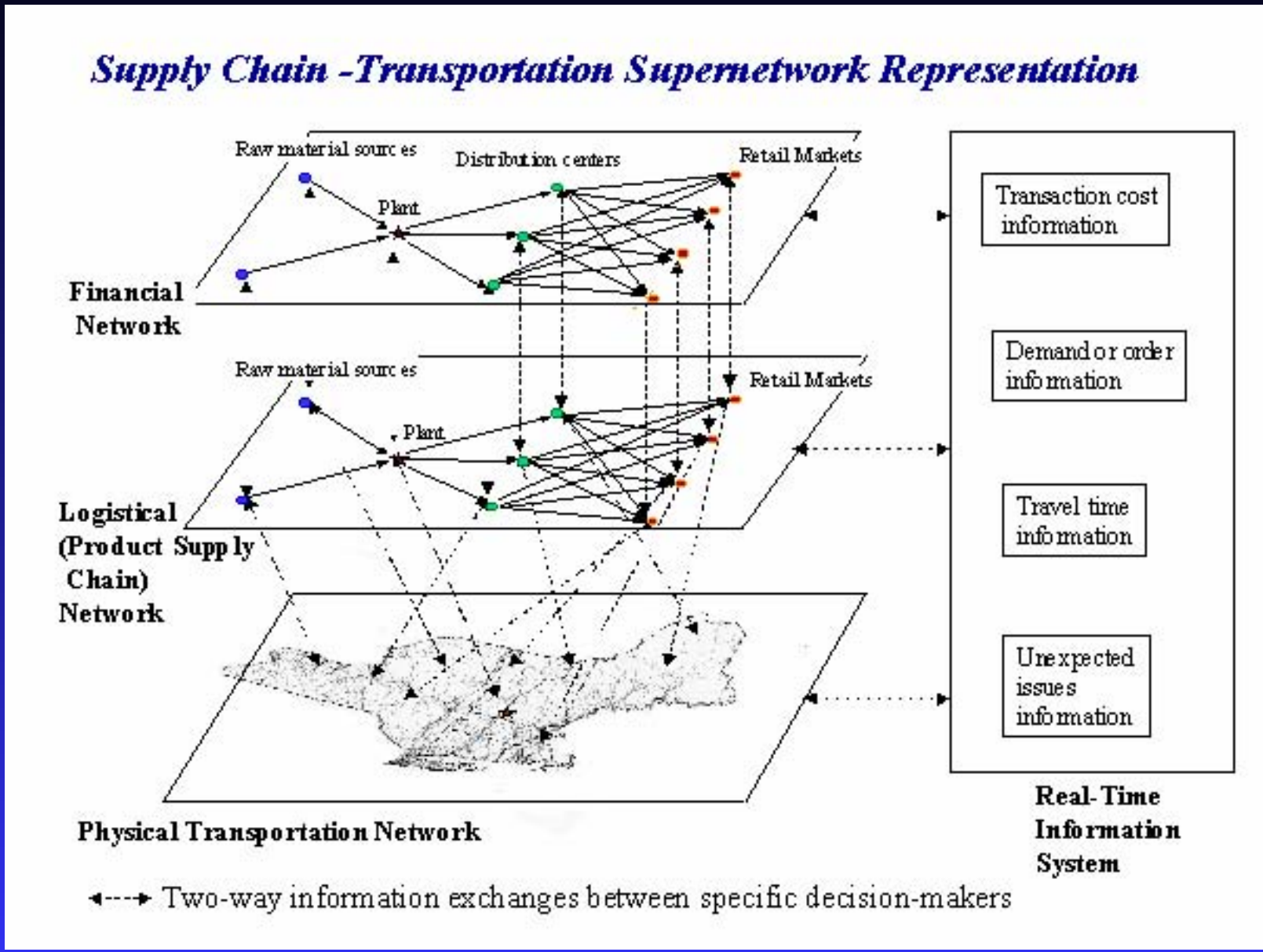
Network Components



The components of networks as a theoretical (modeling, analysis, and solution) construct include: nodes, links, and flows.

We use such a representation to conceptualize, formulate, and study network systems in the real-world.

Representation of Supply Chains as Supernetworks



Why Behavior Matters and Paradoxes

Network Models from Analysis to Design Must Capture the Behavior of Users

The Braess Paradox Illustrates Why

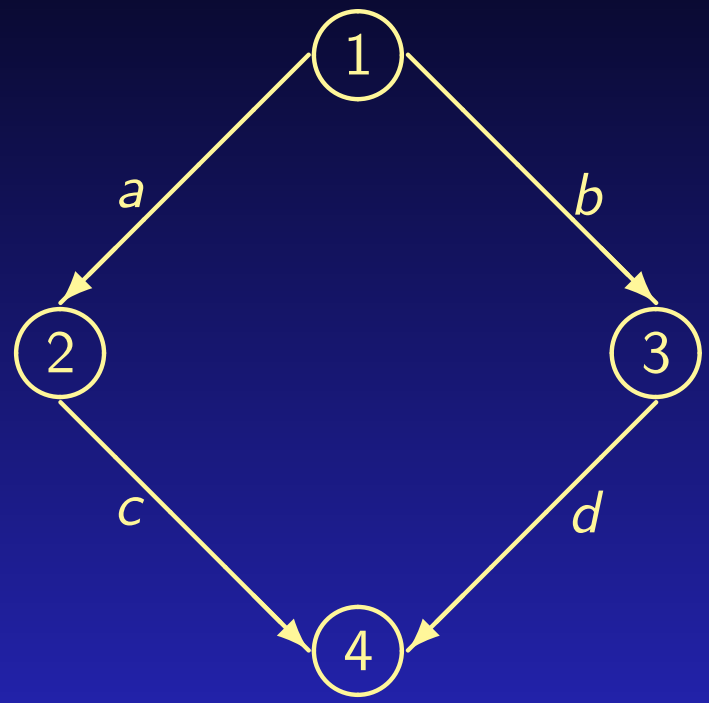
Capturing the Behavior of Users on Networks is Critical

Importance of Capturing Behavior on Networks
Braess Paradox and User-Optimizing 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 $C_{p_1} = C_{p_2} = 83$.



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

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

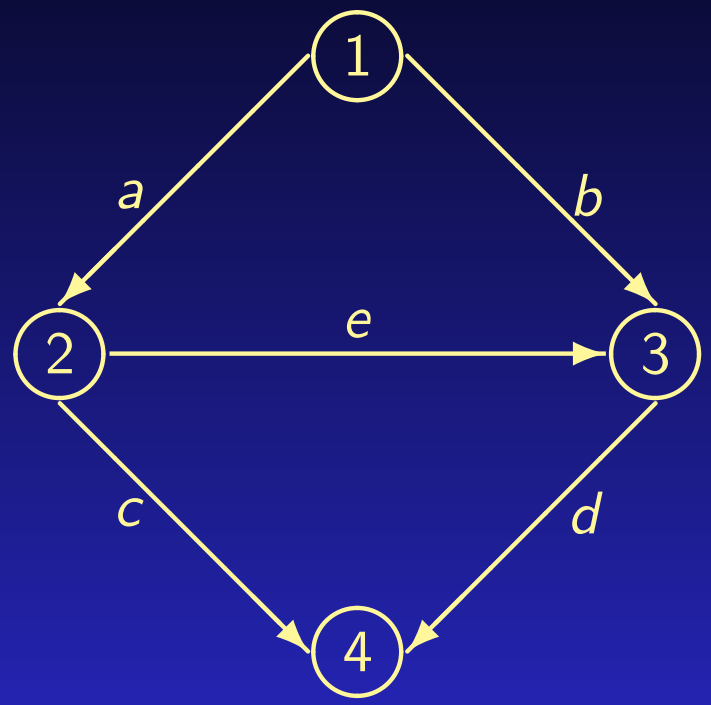
Adding a Link Increases Travel Cost for All!

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

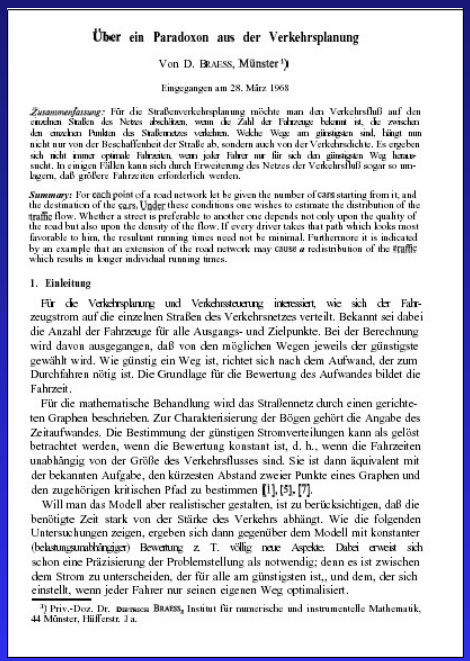


$c_e(f_e) = f_e + 10$

The 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.

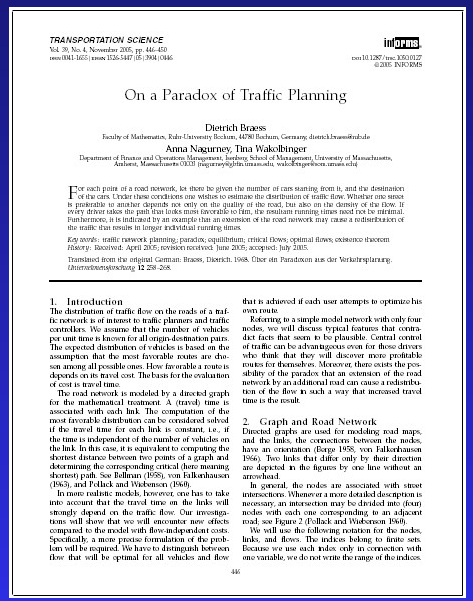
1. Einleitung

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.



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On a Paradox of Traffic Planning

Dietrich Braess
Faculty of Mathematics, Ruhr-University Bochum, 44780 Bochum, Germany, dietrich.braess@rub.de
Anna Nagurney, Tina Wakolbinger
Department of Finance and Operations Management, Isenberg School of Management, University of Massachusetts, Amherst, Massachusetts 01003 {nagurney@gbfin.umass.edu, wakolbin@som.umass.edu}

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 controllers. We assume that the number of vehicles per unit time is known for all origin-destination pairs. The expected distribution of vehicles is based on the assumption that the most favorable routes are chosen among all possible ones. How favorable a route is depends on its travel cost. The basis for the evaluation of cost is travel time.

The road network is modeled by a directed graph for the mathematical treatment. A (travel) time is associated with each link. The computation of the most favorable distribution can be considered solved if the travel time for each link is constant, i.e., if the time is independent of the number of vehicles on the link. In this case, it is equivalent to computing the shortest distance between two points of a graph and determining the corresponding critical (here meaning shortest) path. See Bellman (1958), von Falkenhausen (1963), and Pollack and Wiebenson (1960).

In more realistic models, however, one has to take into account that the travel time on the links will strongly depend on the traffic flow. Our investigations will show that we will encounter new effects compared to the model with flow-independent costs. Specifically, a more precise formulation of the problem will be required. We have to distinguish between flow that will be optimal for all vehicles and flow that is achieved if each user attempts to optimize his own route.

Referring to a simple model network with only four nodes, we will discuss typical features that contradict facts that seem to be plausible. Central control of traffic can be advantageous even for those drivers who think that they will discover more profitable routes for themselves. Moreover, there exists the possibility of the paradox that an extension of the road network by an additional road can cause a redistribution of the flow in such a way that increased travel time is the result.

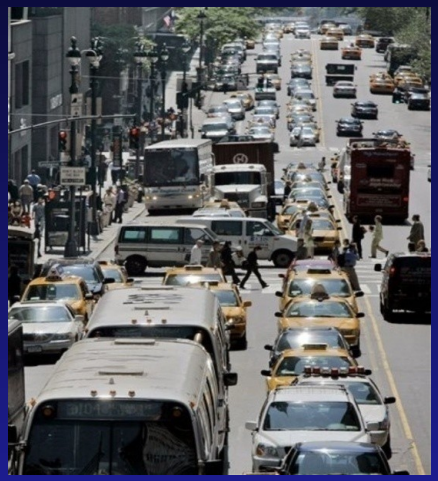
2. Graph and Road Network

Directed graphs are used for modeling road maps, and the links, the connections between the nodes, have an orientation (Berge 1958, von Falkenhausen 1966). Two links that differ only by their direction are depicted in the figures by one line without an arrowhead.

In general, the nodes are associated with street intersections. Whenever a more detailed description is necessary, an intersection may be divided into (four) nodes with each one corresponding to an adjacent road; see Figure 2 (Pollack and Wiebenson 1960).

We will use the following notation for the nodes, links, and flows. The indices belong to finite sets. Because we use each index only in connection with one variable, we do not write the range of the indices.

The Braess Paradox Around the World

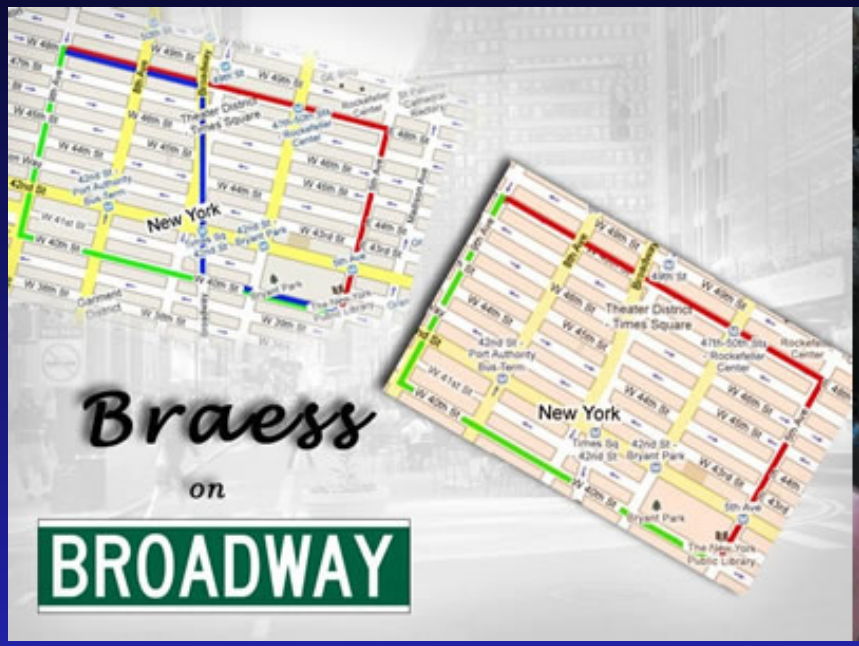


1969 - Stuttgart, Germany - The traffic worsened until a newly built road was closed.

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

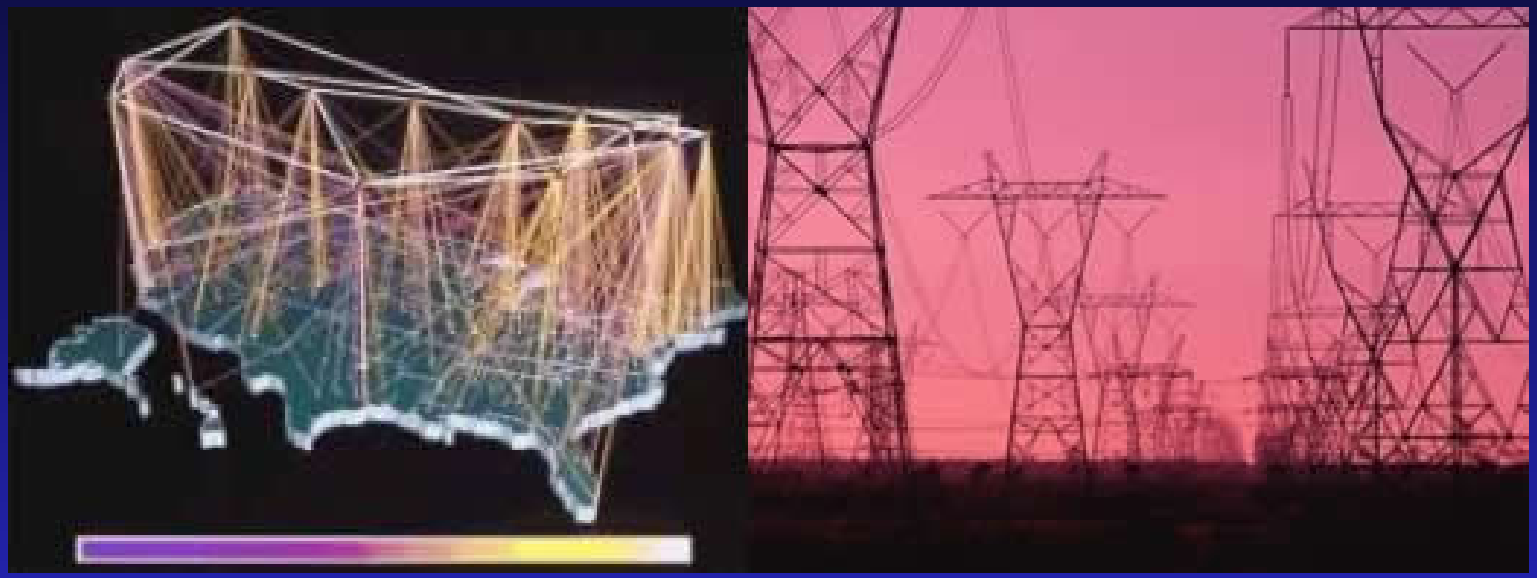
2002 - Seoul, Korea - A 6 lane road built over the Cheonggyecheon River that carried 160,000 cars per day and was perpetually jammed was torn down to improve traffic flow.

Braess on Broadway in NYC and Interview



Broadway between 42nd and 47th Street was converted to a pedestrian plaza.

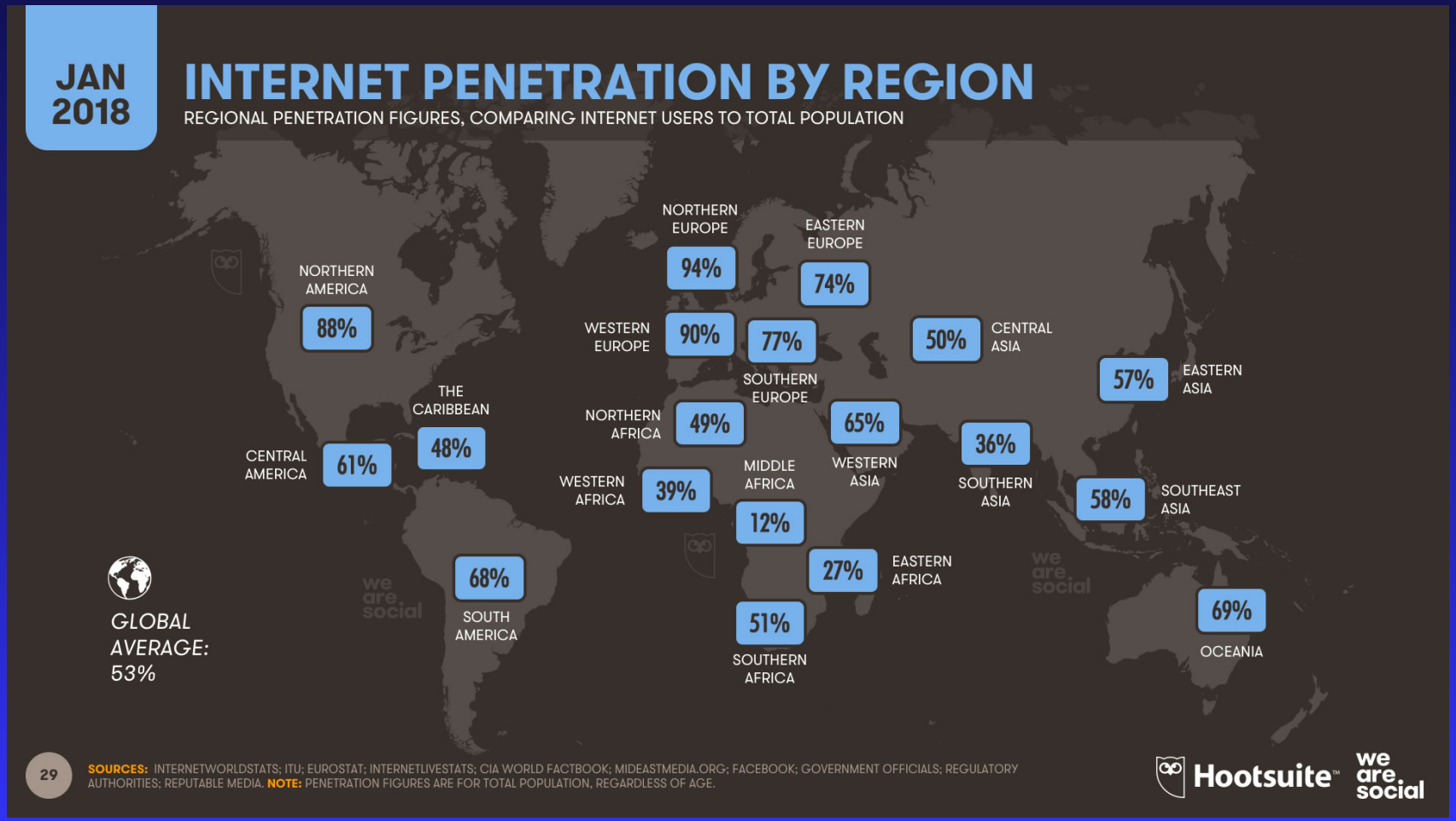
Other Networks that Behave in a Similar Manner



The Internet and Electric Power Networks!

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



Envisioning a New Kind of Internet – ChoiceNet

Envisioning a New Kind of Internet – ChoiceNet

We were one of five teams funded by the US National Science Foundation as part of the Future Internet Architecture (FIA) project. Our project: *Network Innovation Through Choice* envisions a new Internet architecture *ChoiceNet*.

Team:

- University of Massachusetts Amherst: Tilman Wolf, Anna Nagurney
- University of Kentucky: Jim Griffioen, Ken Calvert
- North Carolina State University: Rudra Dutta, George Rouskas
- RENCI/UNC: Ilya Baldin

Some Weaknesses of Current Internet

- **The Internet architecture lacks 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**.

- **Routing of messages may be inefficient** and **the capacity is not well-utilized in the network**.

ChoiceNet Foci: *Choices* **and** *Network Economics*

Choice criteria can include:

- **privacy**
- **minimization of risk**
- even **reducing environmental impact**.

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

ChoiceNet Principles

Competition Drives Innovation!

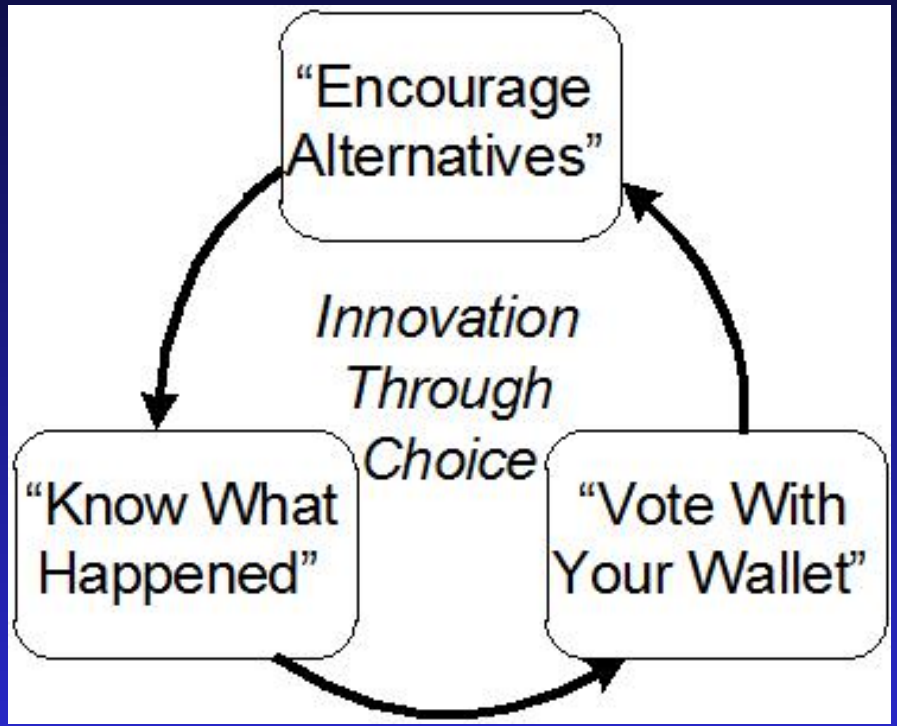
Services are at core of ChoiceNet ("everything is a service")

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!

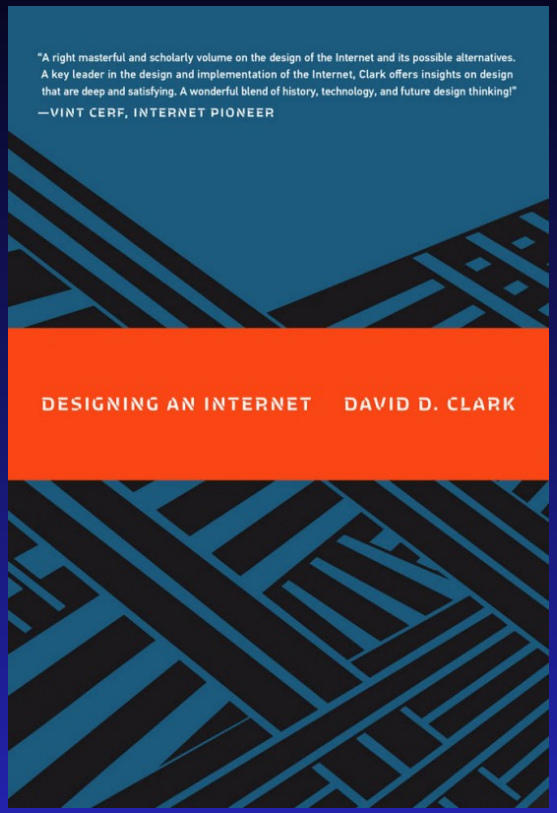


ChoiceNet

- **ChoiceNet / economy plane enables new business models in the Internet**
  – Very dynamic economic relationships are possible
  – All entities get rewarded.

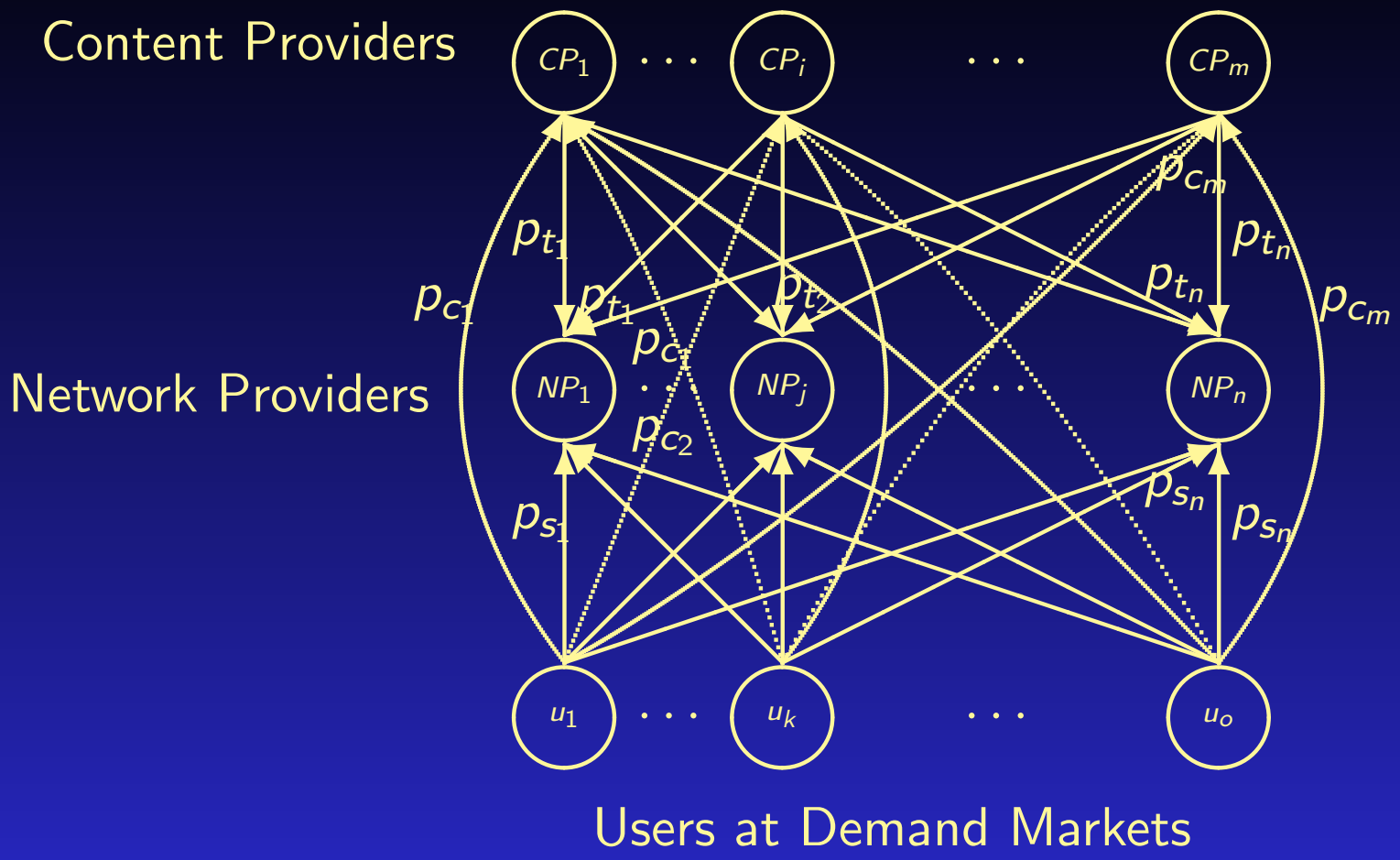
- **Examples**
  – Movie streaming
  – Reading a newspaper online in a coffee shop (short-term and long-term contracts)
  –Customers as providers.

Designing an Internet



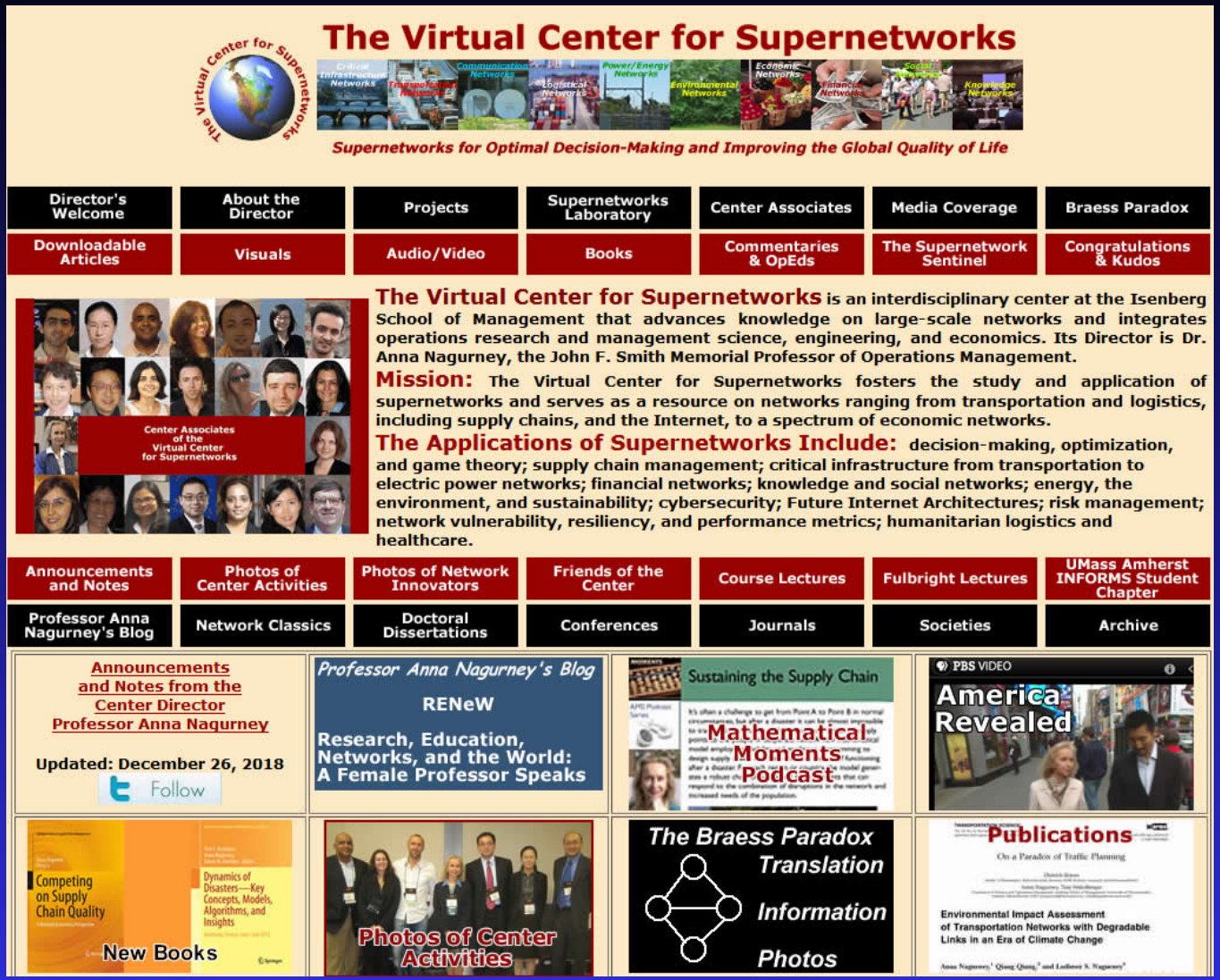
The new book by Clark, a developer of the Internet, cites our paper: "ChoiceNet: Toward an Economy Plane for the Internet," Wolf, Griffioen, Calvert, Dutta, Rouskas, Baldin, and Nagurney, *ACM SIGCOMM Computer Communication Review* **44(3)** (2018), pp 58-65.

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!



For more information, see: http://supernet.isenberg.umass.edu