The Traffic Circle of Life

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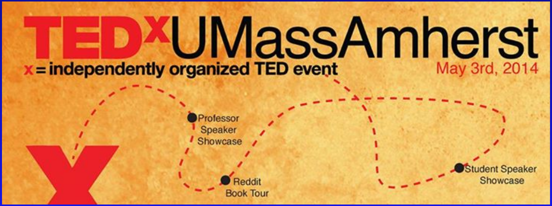
TEDxUMassAmherst, Professor Speaker Showcase
November 25, 2013



Special thanks to the organizers of this very special event – it is an honor to be here tonight.

Also, sincerest thanks to all the great students at UMass Amherst, present, past, and future who continue to think past boundaries and build bridges across disciplines.

Life is about *Choices*:

- from which college to attend
- to which major you pick
- to the job offer that you accept or grad school that you go to,
- to where you decide to live (and with whom), and even
- to the mode of transport you chose to get to this event tonight and the route that you took.

And the choices that you make affect not only you but others who are journeying with you through the various networks.

We Are in a New Era of Decision-Making Characterized by:

- *complex interactions* among decision-makers in organizations;
- *alternative and, at times, conflicting criteria* used in decision-making;
- *constraints on resources*: human, financial, natural, time, etc.;
- *global reach* of many decisions;
- *high impact* of many decisions;
- *increasing risk and uncertainty*;
- the *importance of dynamics* and realizing a timely response to evolving events.

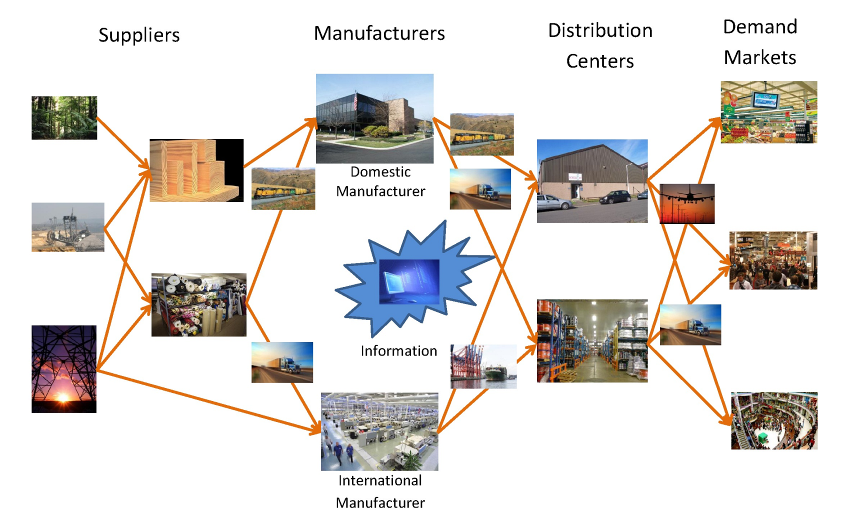
The Era of Supernetworks

Supernetworks are *Networks of Networks*, and their prevalence in the world around us is illustrated by:

- *multimodal transportation networks*;
- *complex supply chain networks consisting of manufacturers, shippers and carriers, distributors, and retailers*;
- *electric power generation and distribution networks*,
- *multitiered financial networks*, and
- *social network platforms such as Facebook and Twitter*, along with the Internet itself.

Multimodal Transportation

Complex Supply Chain Networks

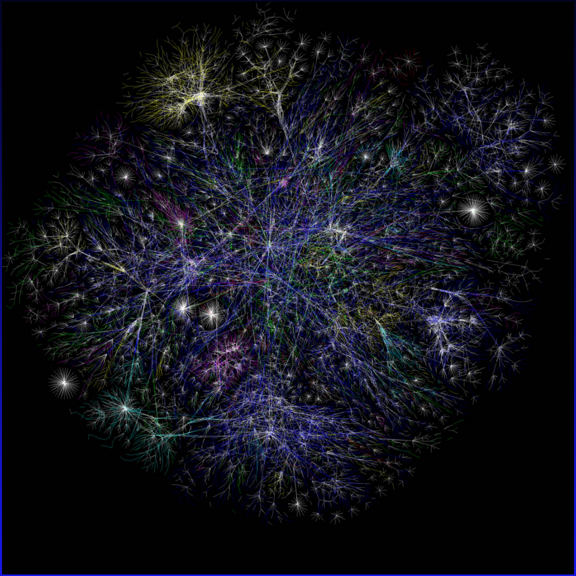


Electric Power Generation and Distribution Networks

Financial Networks

Social Networks

Visual Image of the Internet (opte.org)

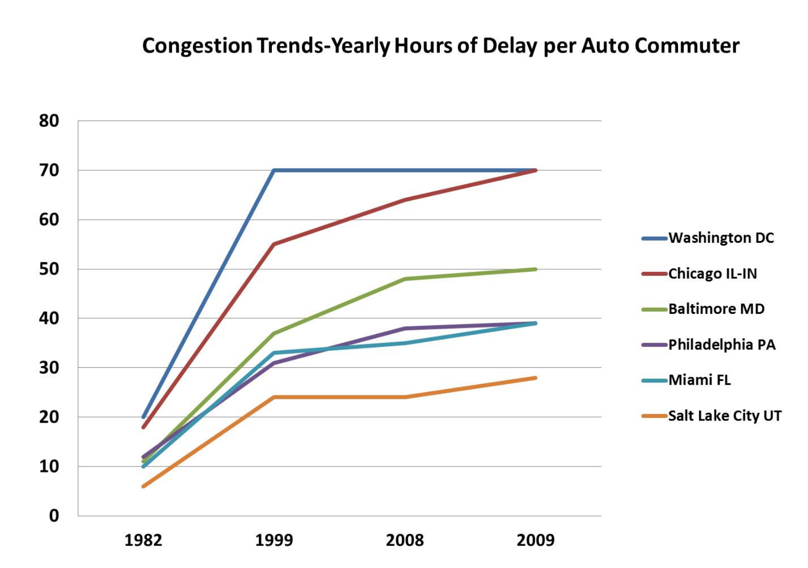


Characteristics of Networks Today

Characteristics of 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, financial, 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*.

Congestion Delay for Commuters

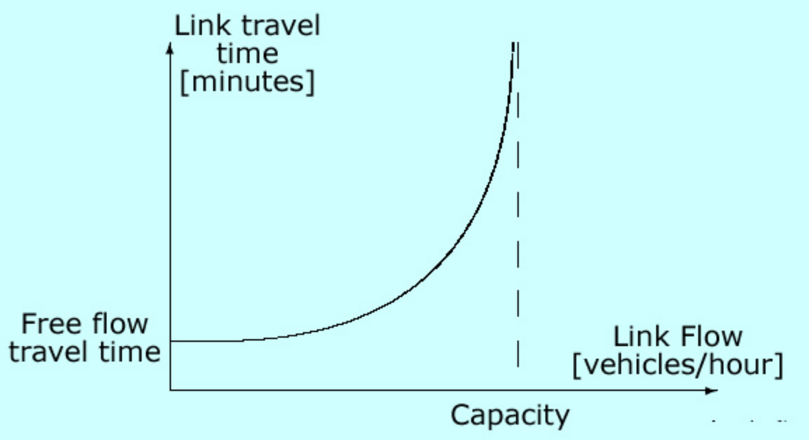


Congestion costs continue to rise: *the cost of congestion has risen from $24 billion in 1982 to $121 billion in 2011 in the United States.*

The average commuter spent an extra 38 hours traveling in 2011, up from 16 hours in 1982. In areas with over 3 million persons, commuters experienced an average of 52 hours of delay in 2011.

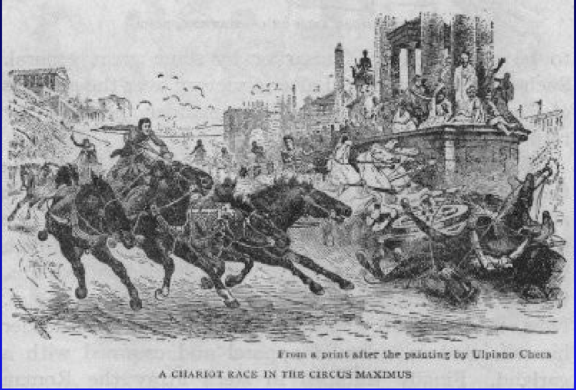
In 2011, *2.9 billion gallons of wasted fuel – enough to fill 4 New Orleans Superdomes.*

Capturing Link Congestion



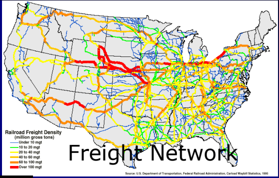
Congestion is Not a New Phenomenon

The study of the efficient operation of transportation networks dates to ancient Rome. The Romans instituted a *time of day chariot policy*, whereby chariots were banned from Rome at particular times of day.



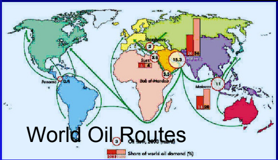
Congestion as the West was Won

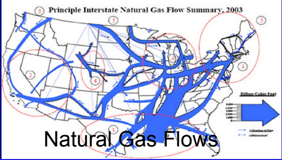
Some Network Systems



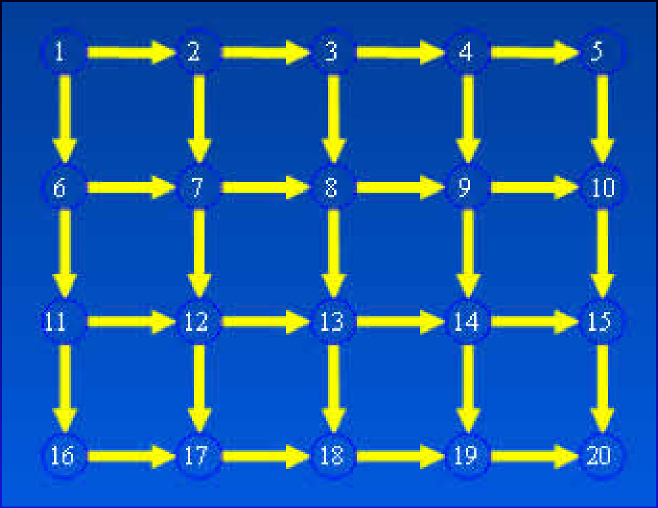
Network

Systems





Network Components



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

Interdisciplinary Impact of Networks

Models and Algorithms

Networks

Economics and Finance

Interregional Trade

General Equilibrium

Industrial Organization

Portfolio Optimization

Flow of Funds Accounting

OR/MS and Engineering

Energy

Manufacturing

Telecommunications

Transportation

Supply Chains

Sociology

Social Networks

Organizational Theory

Computer Science

Routing Algorithms

Price of Anarchy

Biology

DNA Sequencing

Targeted Cancer Therapy

Why Behavior Matters and Paradoxes

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

Behavior on Congested Networks

Flows are routed on individual cost-minimizing routes.

		User-Optimized or Equilibrium
Decentralized	Selfish	U–O
vs. ⇔	vs. ⇔	vs.
Centralized	Unselfish	S–O
		System-Optimized

Flows are routed so as to minimize the total cost.

Two fundamental principles of flow (traffic) behavior, due to Wardrop (1952), with terms coined by Dafermos and Sparrow (1969).

User-optimized (U-O) (network equilibrium) Problem – each user determines his/her cost-minimizing route of travel between an origin/destination, until an equilibrium is reached.

System-optimized (S-O) Problem – users are allocated among the routes so as to minimize the total cost in the system.

We Can State These Conditions Mathematically!

The U-O and S-O Conditions

Definition: U-O or Network Equilibrium – Fixed Demands
A path flow pattern x^**, with nonnegative path flows and O/D pair demand satisfaction, is said to be U-O or in equilibrium, if the following condition holds for each O/D pair* $w \in W$ *and each path* $p \in P_w$*:*

$$C_p(x^*) \begin{cases} = \lambda_w, & \text{if} \quad x_p^* > 0, \\ \geq \lambda_w, & \text{if} \quad x_p^* = 0. \end{cases}$$

Definition: S-O Conditions
A path flow pattern x with nonnegative path flows and O/D pair demand satisfaction, is said to be S-O, if for each O/D pair $w \in W$ and each path $p \in P_w$:

$$\hat{C}'_p(x) \begin{cases} = \mu_w, & \text{if} \quad x_p > 0, \\ \geq \mu_w, & \text{if} \quad x_p = 0, \end{cases}$$

where $\hat{C}'_p(x) = \sum_{a \in \mathcal{L}} \frac{\partial \hat{c}_a(f_a)}{\partial f_a} \delta_{ap}$, and μ_w is a Lagrange multiplier.

The Braess Paradox Illustrates

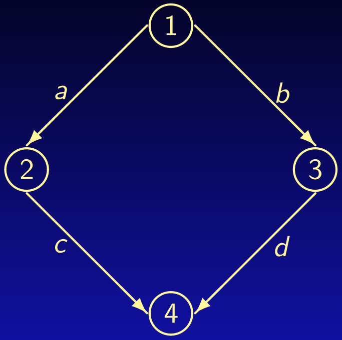
Why Behavior on Networks is Important

The Braess (1968) 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 $C_{p_1} = C_{p_2} = 83$.



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

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

Adding a Link Increases Travel Cost for All!

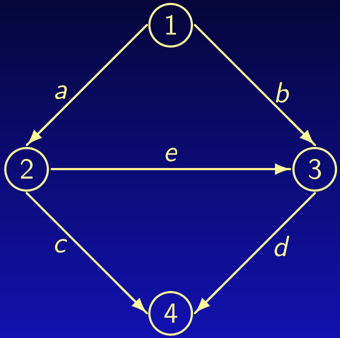
Adding a new link creates a new path $p_3 = (a, e, d)$.

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



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

Under S-O behavior, the total cost in the network is minimized, and the new route p_3, under the same demand of 6, would not be used.

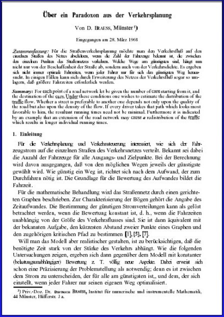
The Braess paradox never occurs in S-O networks.

Braess Comes to the Isenberg School at UMass Amherst

The 1968 Braess article has been translated from German to English and appears as:

"On a Paradox of Traffic Planning,"

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

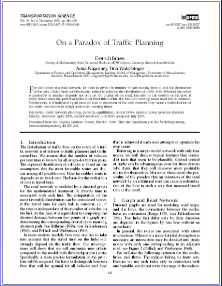
1. Einleitung

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

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On a Paradox of Traffic Planning

Dietrich Braess

Anna Nagurney, Tina Wakolbinger

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.

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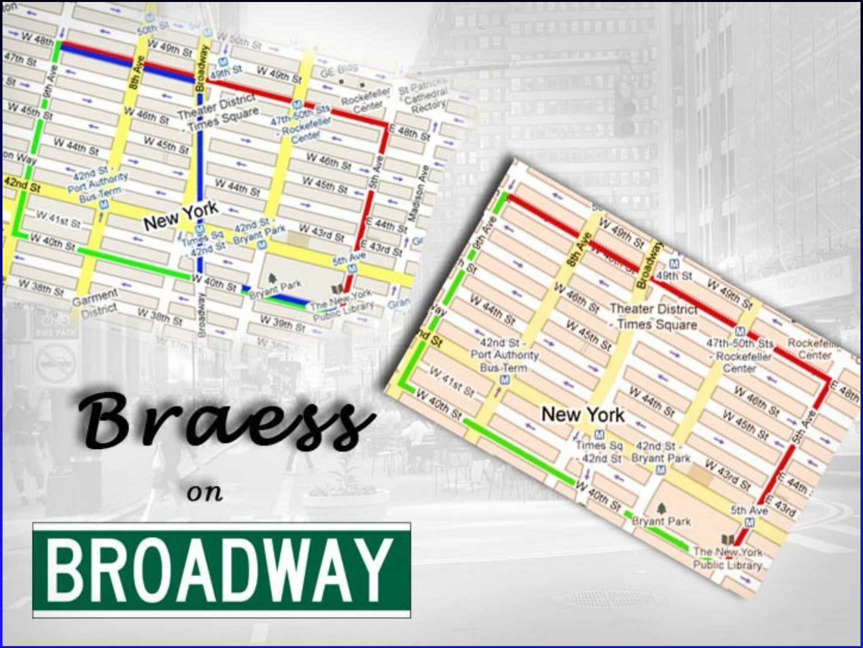
The Braess Paradox Around the World

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

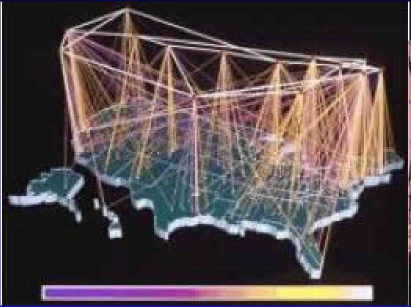
1990 - Earth Day - New York City - 42^{nd} Street was closed and traffic flow improved.

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.

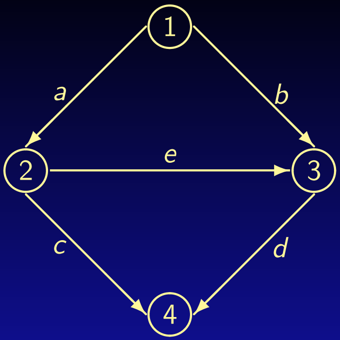

Braess
on
BROADWAY
W 48th
W 49th St
Broadway
8th Ave
9th Ave
W 46th St
Theater District
- Times Square
47th-50th Sts
- Rockefeller
Center
Rockefeller
Center
E 48th St
W 44th St
W 45th St
42nd St -
Port Authority
Bus Term
New York
W 41st St
W 40th St
Times Sq
- 42nd St
42nd St -
Bryant Park
W 43rd St
5th Ave
E 44th St
E 43rd St
Bryant Park
The New York
Public Library
W 38th St
W 39th St
Garment
District
49th St
W 50th St
GE Bldg
St Patrick's
Cathedral
Rectory
Madison Ave
42nd St

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

Other Networks that Behave like Traffic Networks



The Internet, electric power networks, supply chains, and even multitiered financial networks!



Recall the Braess network with the added link e.

What happens as the demand changes over time?

For Networks with Time-Dependent Demands

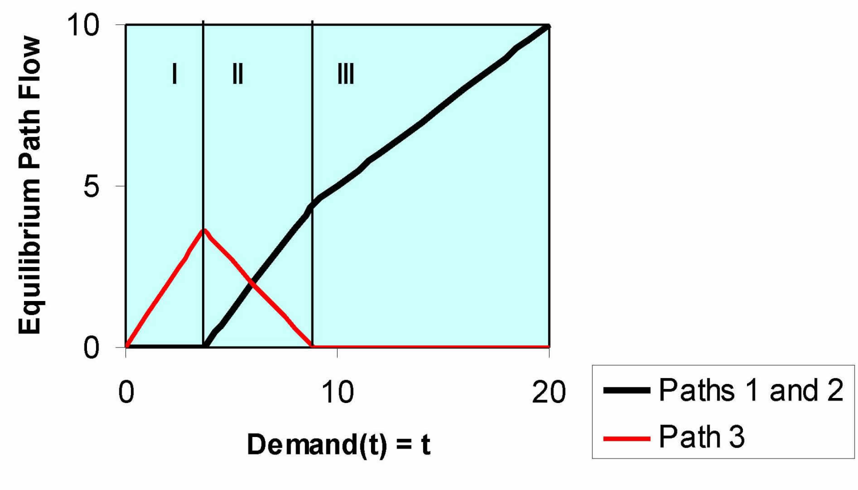
We Use Evolutionary Variational Inequalities

Radcliffe Institute for Advanced Study – Harvard University 2005-2006

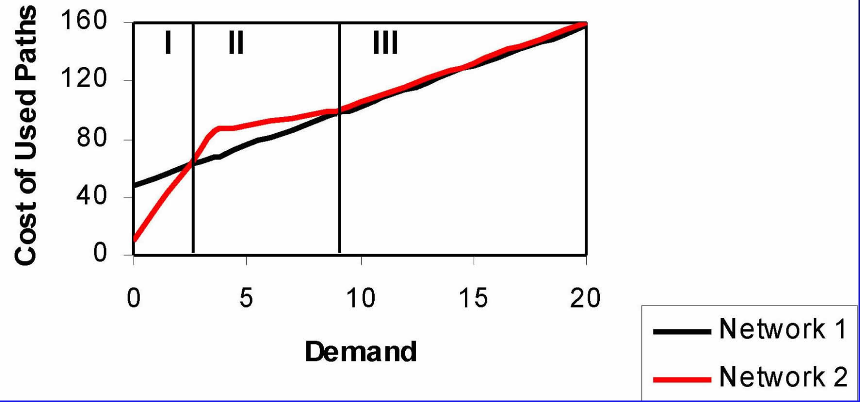
 

Research with Professor David Parkes of Harvard University and Professor Patrizia Daniele of the University of Catania, Italy

The U-O Solution of the Braess Network with Added Link (Path) and Time-Varying Demands Solved as an *Evolutionary Variational Inequality* in a Model of the Internet (Nagurney, Daniele, and Parkes (2007)).



In Demand Regime I, Only the New Path is Used.
In Demand Regime II, the 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 demand exceeds 8.89, *Only the Original Paths are Used!*

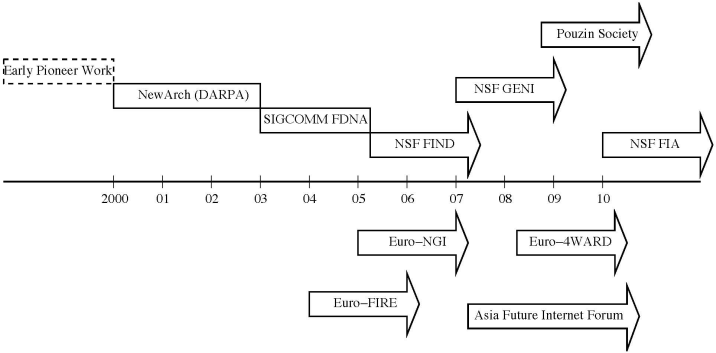


The new path is never used, under U-O behavior, when the demand exceeds 8.89, even out to infinity!

From Transportation to the Internet

Evolution of the Internet

Historical Perspective



3

The Existing Internet

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However, the Internet offers little choice of service inside the network.

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Much of the Internet's success comes from its ability to support a wide range of service at the edge of the network.

However, the Internet offers little choice of service inside the network.

It is widely agreed that this limitation inhibits the development and deployment of new networking services, protocols, security designs, management frameworks, and other components that are essential to support the increasingly diverse systems, applications, and communication paradigms of the next-generation Internet.

Envisioning a New Kind of Internet – ChoiceNet

Envisioning a New Kind of Internet

We are one of five teams funded by NSF as part of the Future Internet Architecture (FIA) project.

Our project is: *Network Innovation Through Choice* and the envisioned architecture is *ChoiceNet* with UMass Amherst as the lead.

Team:

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

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.

ChoiceNet Principles

Competition Drives Innovation!

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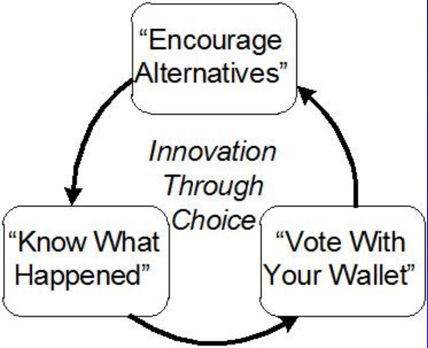
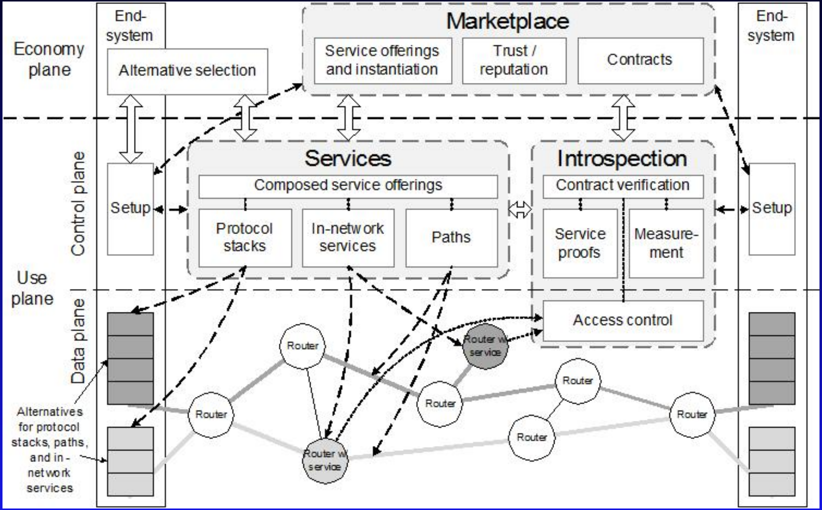
"Encourage alternatives" Provide building blocks for different types of services

"Know what happened" Ability to evaluate services

"Vote with your wallet" Reward good services!



ChoiceNet 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

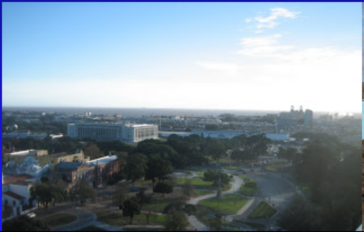
– Movie streaming
– Reading *The New York Times* and *The Boston Globe* in a coffee shop (short-term and long-term contracts)
–Customers as providers.

Places that Working on Networks Will Take You

Places that Working on Networks Will Take You

Yalta, Ukraine with my taxi driver Igor

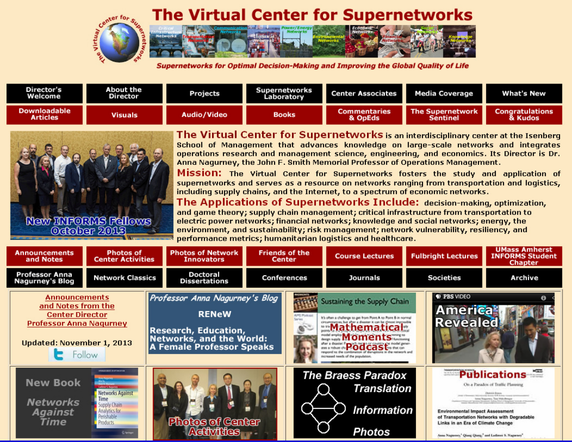

Buenos Aires, Argentina and the Blue Lagoon in Rejkyavik, Iceland




The Traffic Circle of Life

Enjoy the Journey

Thank You!



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