National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

INFORMATION TECHNOLOGY LABORATORY

Some Personal Observations on System Complexity

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Outline

Warning: we do not discuss algorithmic (Kolmogorov) Complexity

General observations

- System Complexity vs. Network Complexity
- Complexity management vs. reduction/containment

Complexity of bandwidth sharing

- Single path TCP/IP Complexity management - Conex
- Multipath TCP/IP (MPTCP) Complexity management - ?

Price of Anarchy as a Measure of Multipath Complexity Risks

- Cascading failures
- Asymmetric threats

NIST – Bell Labs Workshop on Complex Networks:
Network Curvature as a measure of Network Complexity

Conclusion

IRTF Network Complexity Research Group (NCRG)

The NCRG aims at defining and analyzing the complexity of IP-based networks.

Complexity has been researched from a number of different angles, for example software complexity, or graph complexity. There is however no good, objective understanding of the complexity of a real IP network, including its operational aspects. When two competing approaches (e.g., protocols, network architectures) are discussed there is generally no measurable metric for complexity.

It would be highly desirable to have such metrics for network complexity to objectively compare IP networking approaches. The goal of this research group is to gain a better understanding of the underlying metrics of network complexity.

The NCRG provides objective definitions, metrics and background research to help making decisions where complexity is a factor. The ultimate goal is to provide factual and objective information and metrics to be used in network and protocol design. It is highly desirable to have practical and objective information on network complexity as an input into the IETF process.

Areas of interest include:

- Definitions of "***network complexity***" and relevant metrics.
- Quantification of the complexity of various network architectures, protocols or approaches.
- Methods and ideas to ***contain, control, or reduce*** complexity in IP based networks.
- Documenting cases of specific network design or failure where complexity played a role.

System Complexity vs. Network Complexity

End-to-end principle for IP networks

	Core Network	Peripheral Devices/Users
Telephone Network	Smart/Complex	Damn Telephones
IP Network	Damn - Transport	Smart/Complex - Computers

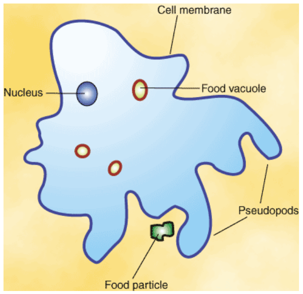
Our contention: instead of IP network complexity we should care about System Complexity, where System = core network & end user behavior:

System Complexity = Complexity(core network & end user behavior)

This idea has been proposed by David Clark, Craig Partridge , J. Christopher Ramming† and John T. Wroclawski, in seminal Sigcomm'03 paper "A knowledge Plane for the Internet,":
"…Adding complexity to the core may reduce system complexity…"
Added complexity may include:

- Fault diagnosis and mitigation
- Automatic reconfiguration
- Support for overlay network
- Knowledge-enhanced intrusion detection

Complexity Management vs. Complexity Containment

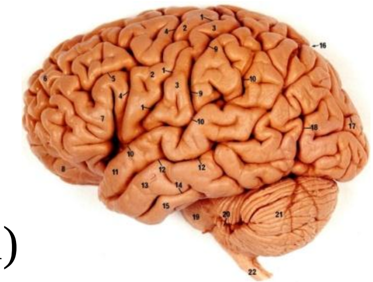


http://www.sparknotes.com/biology/microorganism/s/

Scale of complexity in Nature

rigid, predictable

flexible, adjustable
Unpredictable (free will)



professorherm.wordpress.com/2010/05/

Lessons:

- Evolution does not contain or reduce Complexity
- Complexity has value, e.g., flexibility and adjustability

Conundrum:

- We need Complexity for its benefits
- Complexity may lead to undesirable behavior

Proposed solution (from Economics):

- Framing the problem as “Managing Complexity”
- Employ methodology of “Risk Management”

Basis: similarities of networks and economies [Frederick Hajek], e.g.,:
Telephone Network – centralized command economy (GOSPLAN)
TCP/IP network – decentralized market economy [Frank Kelly]

Complexity Drivers of Internet Trends

Major Internet trends:

- Bandwidth sharing: from statistical multiplexing on a link (data traffic burstiness - L. Kleinrock) to multipath TCP/IP routing for better load balancing & resilience
- Evolution of End-to-End (E2E) principle (smart peripheral devices, damn core): adding intelligence to core ("Intelligent Plane"), IETF Conex WG

(Controversial) interpretation:

- Growing bandwidth sharing - growing System Complexity
- Evolution of E2E principle – growing Complexity Management capabilities

Thesis: Complexity Management may be insufficient for emerging System Complexity

TCP pitfalls: selfish end-users can "grab" more bandwidth than "fare share" by:

- Playing with TCP parameters and employing new TCP versions
- Opening several TCP connections (sessions)

IETF Congestion Exposure (Conex) WG, 2010 to deal with some of these abuses.
TCP operated for ~20 years for better or worse

Next step of adding Complexity is in progress: IETF Multipath TCP (MPTCP) WG.

Rest of presentation: a case that this step may not be as benign as single path TCP.

- Externalities (indirect impact), Braess paradox, Price of Anarchy
- Cautionary lessons of multipath routing in telephone network
- Undesirable selfish usage of multipath routing under strategic attack

Externalities, Braess Paradox and Price of Anarchy

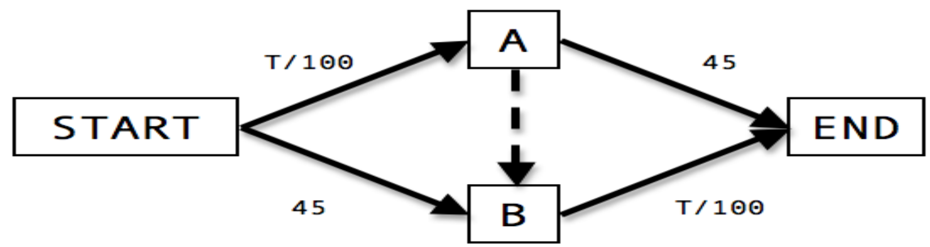
Braess paradox, (1969): infrastructure expansion/redundancy may do harm

4000 selfish travelers choose minimum cost/delay route

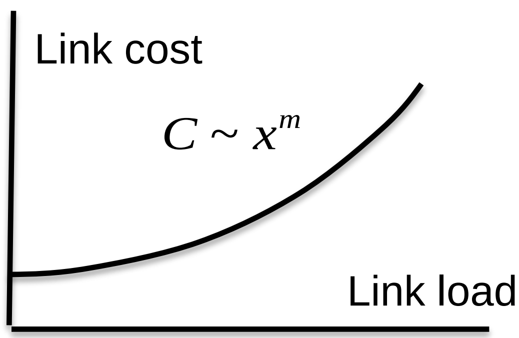
Without link AB:
Delay=2000/100+45=65

After adding link AB:
Delay=4000/100+4000/100=80

Price of Anarchy (PoA) = 80/65



Externalities depend on m:
m=0, no externalities, PoA=1
m>0: negative externalities, PoA>1

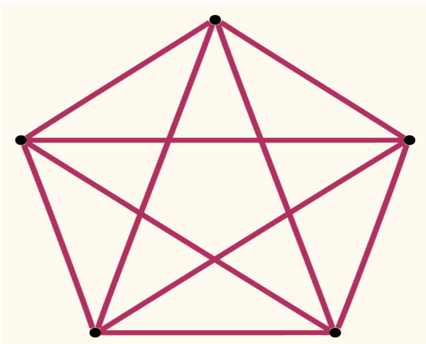


Upper bound for PoA independent of network topology (T. Roughgargen, 2002)

m=1: PoA ~ 1.333
m=2: PoA ~ 1.626
m=3: PoA ~ 1.896
m: PoA ~ m/ln(m)

Resource sharing by selfish agents → externalities → undesired consequences

Cautionary Tales of Phone Network: Loss Network



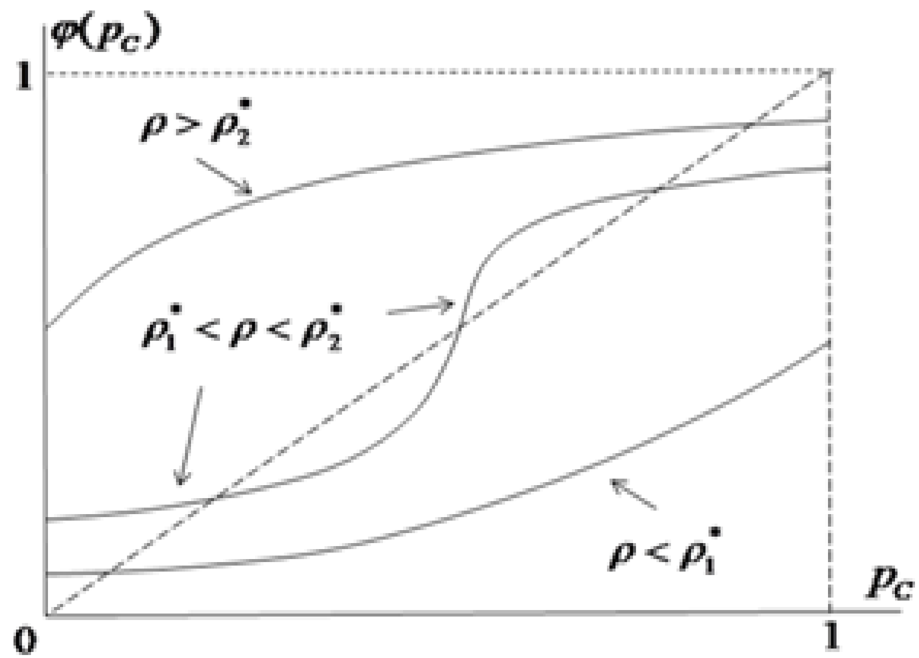
Each link can accommodate C calls , each pair of nodes is connected with probability $1-\pi$, and disconnected with probability π , exogenous link utilization $\rho = \Lambda b / C$, and call loss probability p.

Call routed directly if possible, otherwise 2-link by route is selected.

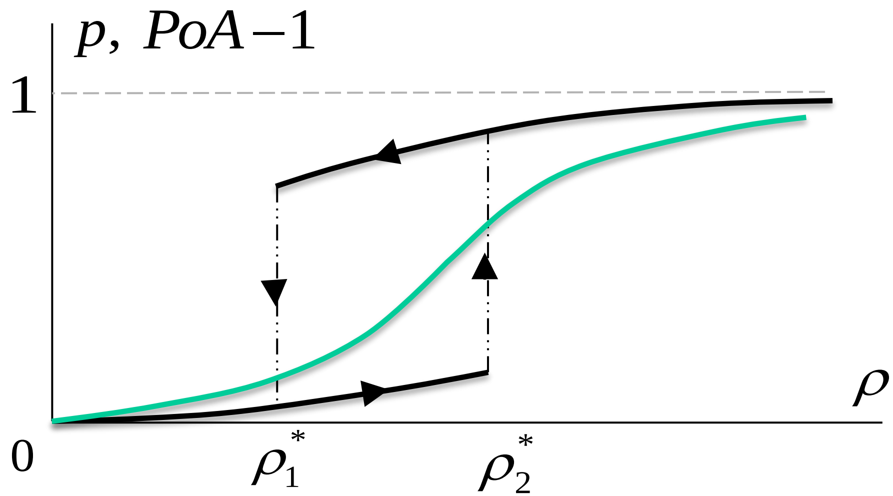
Intuition: alternative routing → negative externalities → positive feedback for transit load → risk of cascading overload.

Mean-field approximation based on hypothesis of chaos propagation leads to the following non-linear fixed-point equation for the probability of a link being completely occupied p_C :

$$p_C = \varphi(p_C | \rho)$$



Multipath & Load Volatility -> Cascading Overload



$0 \le \rho < \rho_1^*$ normal regime is stable
sharing is beneficial

$\rho_1^* \le \rho < \rho_2^*$ normal and overload
regimes are metastable
cascading overload

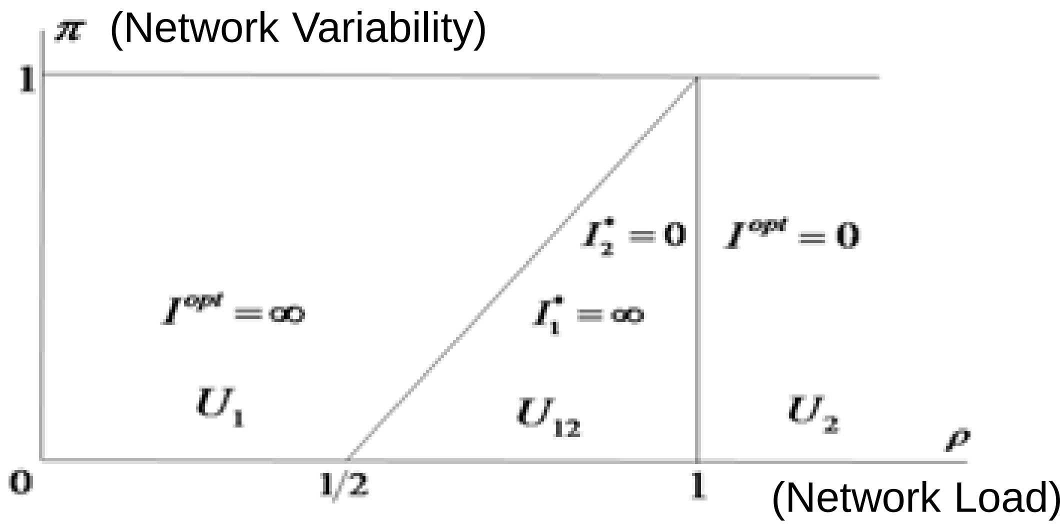
$\rho > \rho_2^*$ overload regime is stable
sharing is harmful

In a practically important region $\rho_1^* \le \rho < \rho_2^*$:
resource sharing (alternate routing) → individual/systemic risk trade-off:
robust (to local overload) yet fragile (to larger scale overload) [J. Doyle]
Oversimplified model of financial system: complex derivatives reduce individual risks but create
and increase systemic risk, e.g., F. Kelly (2010) Institute for New Economic Thinking, Cambridge

Optimally provisioned bandwidth $C = \Lambda b / \rho_2^*$ on the stability boundary $\rho = \rho_2^*$

Lesson: multipath routing & load volatility may lead to cascading overload resulting in high PoA. While for telephone networks this has been confirmed by simulations and observed on real networks, there are theoretical indications that this effect may be even more severe for TCP/IP networks.

Information Availability



Network Phase Diagram:

Agent ability to acquire network-state information is quantified by the number of attempts a flow attempts to find a two-link bypass route to the destination *I.*

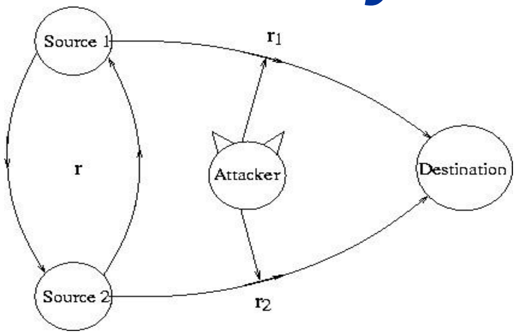
Low load – high uncertainty: $(\rho, \pi) \in U_1$ normal steady state is stable, network state information availability to users is beneficial for overall network performance

High load: $(\rho, \pi) \in U_2$ congested steady state is stable, network state information availability to users is harmful for overall network performance

Intermediate region: $(\rho, \pi) \in U_{12}$ normal and congested steady states are metastable, network state information availability to users is beneficial for overall network performance in normal but harmful in congested steady state.

Lesson: Risks/benefits of multipath routing availability should be managed depending on the exogenous load and network volatility

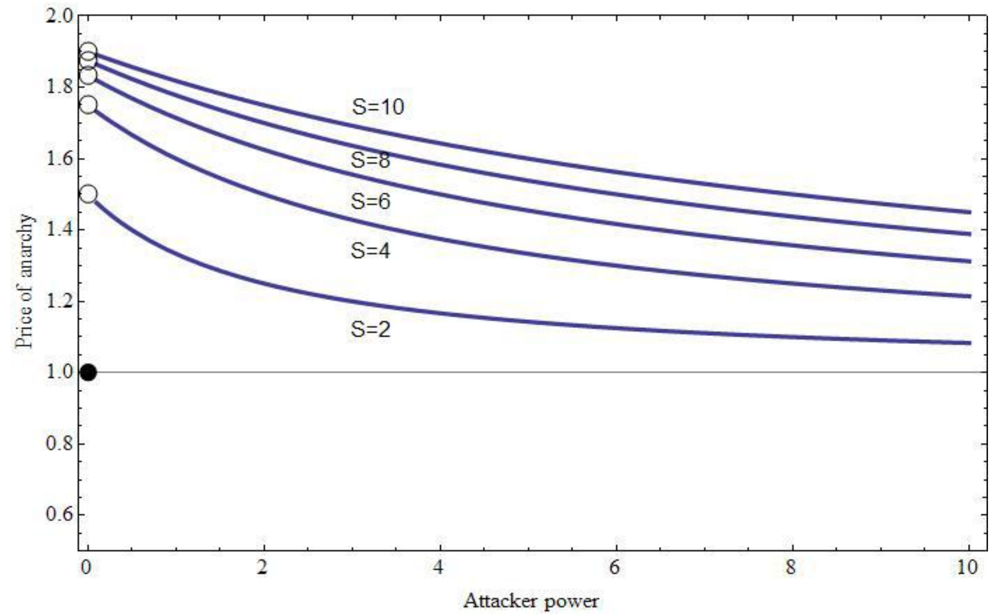
Cautionary Tale: Multipath Routing under Attack



Game-theoretic analysis: D. Genin, V. Marbukh, A. Nakassis (2010)

Attacker can change transportation cost on a direct route from c to $c+h$

PoA vs. attacker power h ➞



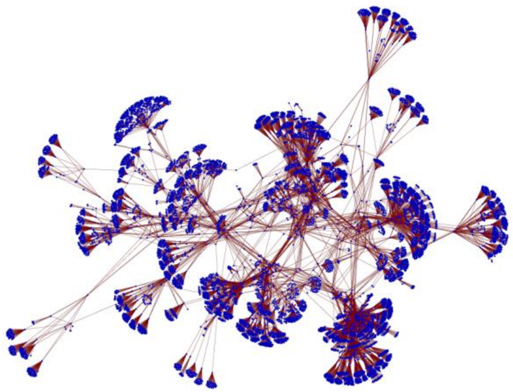
$$PoA = \begin{cases} 1+\dfrac{(S-1)d}{Sc+h} & if \quad h>0 \\ 1 & if \quad h=0 \end{cases}$$

where, # of sources is S, and the cost of a direct link between any two sources is d

Risk of asymmetric Threat: $$RaT = \gamma(+0) = \max_h \gamma(h) = 1 + \frac{S-1}{S}\frac{d}{c}$$

Lesson: Multipath routing may create security risks due to asymmetric adversary(ies)
Challenge: mitigating security threats through combination of incentives, regulations.

Geometry (Curvature) as a Measure of Network Complexity



Hyperbolicity in finite graphs is closely related to strong approximability by trees. Rendering of Rocketfuel AT&T IP-layer network by Narayan-Saniee, *Phys. Rev E,* Dec. 2011.

Conventional paradigm: macroscopic properties are determined by micro-scale geometry such as by node degree distribution. Examples: computer virus propagation (percolation threshold), robustness to attacks, etc.

Emerging paradigm: macroscopic properties are determined by large-scale geometry: dimension, curvature → congestion → externalities → inefficiencies, instabilities,..

To explore we (with Iraj Saniee, Bell Labs, Alcatel-Lucent) organizing

Bell Labs-NIST Workshop on Large-Scale Geometry of Networks,
April 26th, 2011, Murray Hill, New Jersey.
http://ect.bell-labs.com/who/iis/research/workshops/irajSanieeBL-NISTwrkshp4-26-11-nw.pdf
2012 NIST – Bell Labs Workshop on Large-Scale Complex Networks
will be held at NIST on June 8th, 2012

Relevance to NCRG: (a) negative curvature indicates tree-like topology, (b) tree topology - single route, (c) more routes - more complexity → curvature measures complexity.
Intriguing possibility: controlling complexity through curvature
If there is an interest, we may report to NCRG on the relevant 2012 Workshop outcome.

Conclusion

Made general observations on

- System Complexity vs. Network Complexity
- Complexity management vs. reduction/containment

Discussed Complexity of bandwidth sharing

- Single path TCP/IP Complexity management - Conex
- Multipath TCP/IP (MPTCP) Complexity management - ?

Proposed to measure Multipath Complexity Risks by Price of Anarchy and considered examples

- Cascading failures
- Asymmetric threats

Advertised NIST – Bell Labs Workshop on Complex Networks and suggested curvature as a measure of network complexity

Thank you!