A Perspective on Research Directions In Network Science and Engineering

Workshop on Research Challenges for 2015 Global Networks

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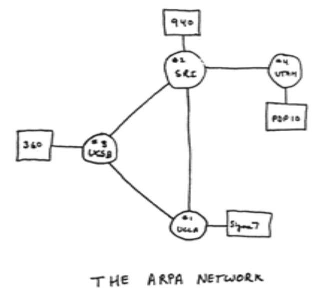
Outline

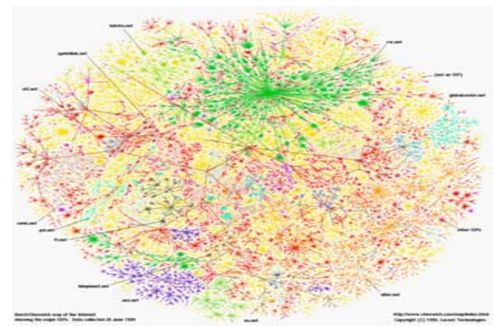
- Background
  - Internet Design Principles and Success
- Future Global Networks: A Case for Network Science and Engineering
  - Science, Architectural and Social Implications
  - Need for Research Infrastructure
- Global Collaboration
- Concluding Remarks

The Internet – A Critical Infrastructure

- ***The Internet has enabled global communication and transformed society***

- ***The Internet will continue to evolve in ways no one anticipated, including the original designers***
  - At the same time, the Internet faces many challenges, not only related to its technical limitations but also to economic and social issues





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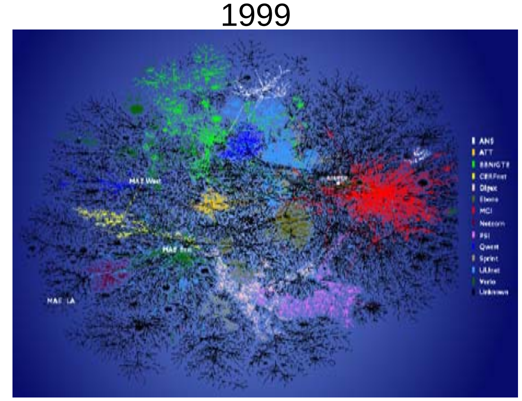


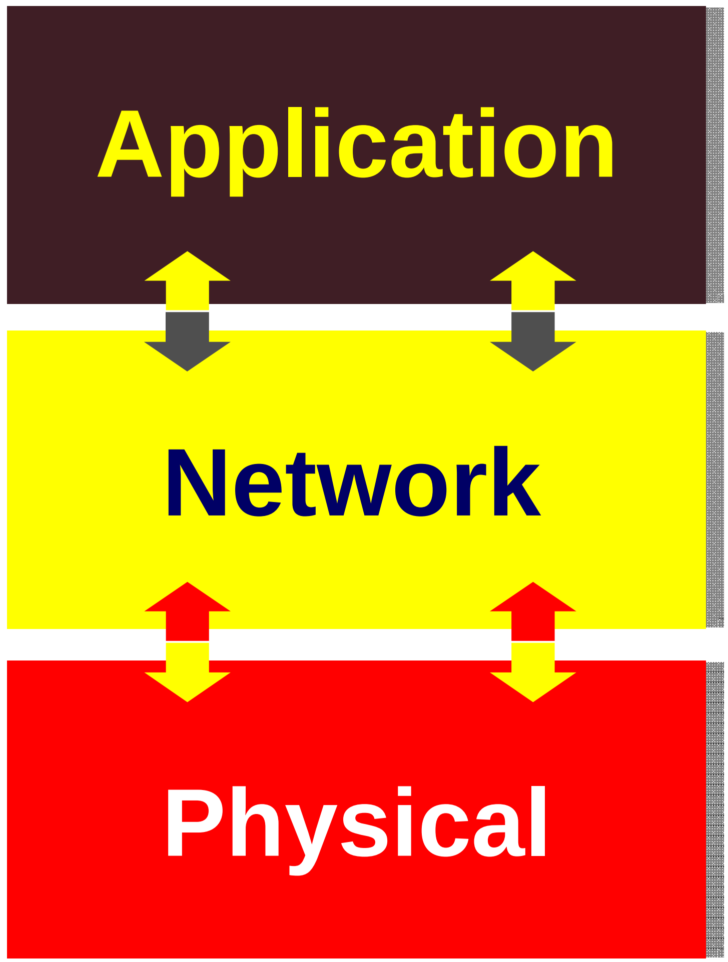
What Made the Internet Incredibly Successful?

Architectural Design Choices and Guiding Principles

Network Design Methodology

- Define overall system goals
- Identity the technological building blocks and associated tradeoffs
- Manage architectural complexity using theoretically grounded design concepts
  - Abstraction and Layering
- Identify and understand the interactions between different components, including their cross-layer designs and implementation optimization
- Decompose system functions across data, control and management plans
  - Organize and assign functions to different planes, appropriately

Network Architecture



Network Design Principles

- Guide the organization and assignment of functions within the system
  - Impose a structure on the design space rather than solve a particular design problem
  - The structure provides a basis for analysis of tradeoffs and a rational for design choices

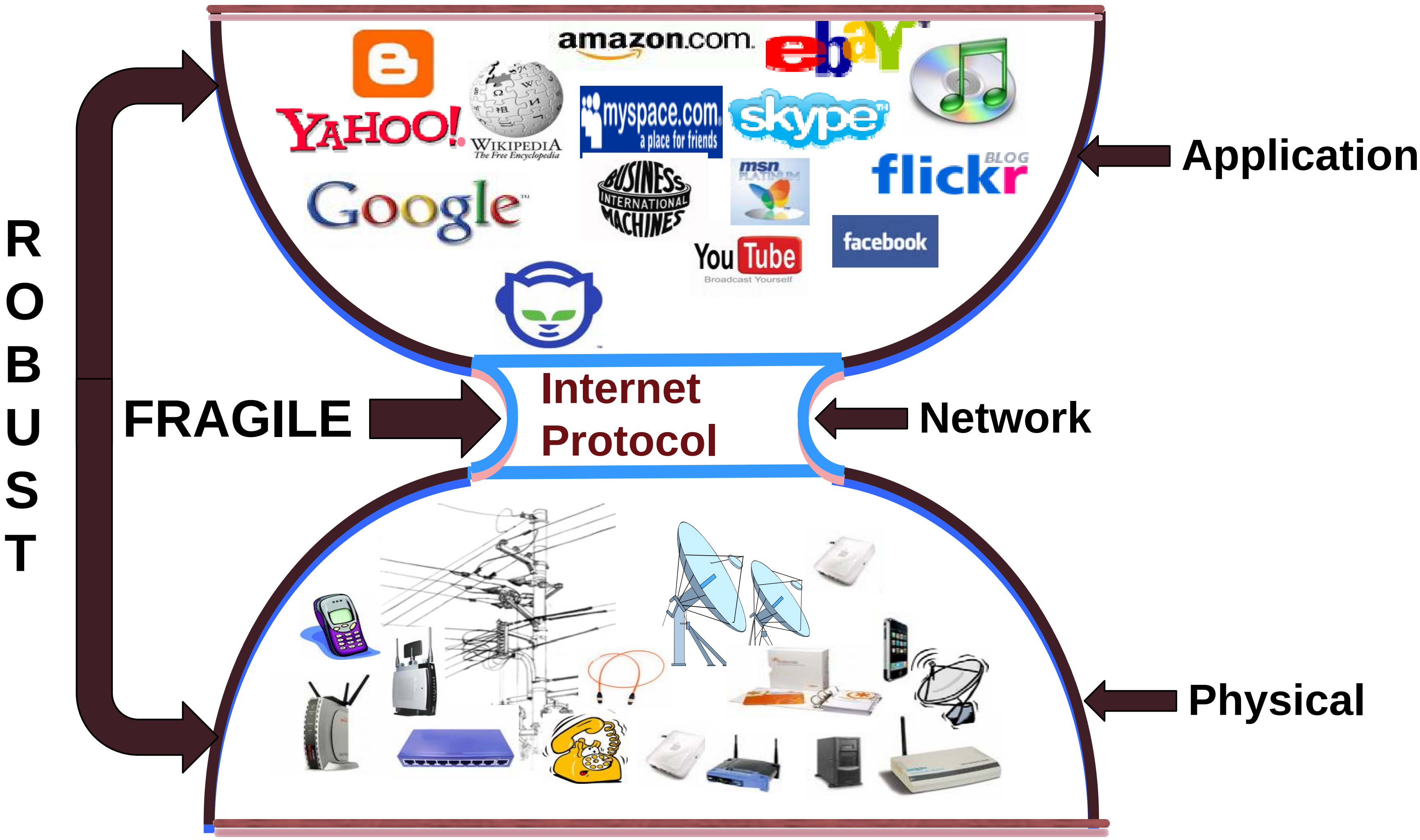
Internet Design Principles

- To achieve robustness, the emphasis on simplicity was a guiding principle of the Internet design.
  - The result is a “light” network core that provides minimal packet level forwarding service
- This minimalistic approach to network design was later justified and generalized into the so called “end-to-end argument”.

End-to-End Argument

- In essence, the argument states that "functions placed at low levels of a system may be redundant or of little value when the cost of providing them at the low level is factored in"
  - A function is provided by a (sub)system only if it can be completely and correctly implemented within it
- What about performance?
  - "… sometimes an incomplete version of the function provided by the communication system may be useful as a performance enhancement"

Internet Architecture



The Internet Explosive Evolution

"… in the thirty-odd years since its invention, new uses and abuses, …, are pushing the Internet into realms that its original design neither anticipated nor easily accommodates."

***Overcoming Barriers to Disruptive Innovation in Networking, NSF Workshop Report, 2005*.**

Complex Socio-Technical Machine!

- From a network of computers to a complex structure of **networked** people communicating spontaneously with **each other** and with their **environments**, creating **content** and sharing **knowledge**, over ubiquitous, **heterogeneous networks** of devices and **physical substrates**

Need for Network Science and Engineering

- As critical as networks are to our lives and diverse sectors of our society, we have little rigorous knowledge when it comes to understanding their structure, dynamics and holistic behaviors.
  - Understanding the complexity of large-scale networks
  - Understand emergent behaviors, local–global interactions, performance degradation and system failure

NetSE Fundamental Challenge

- Is there a **science** for understanding the complexity of our systems such that we can **engineer** them to have predictable behavior, … or at least an adaptable one?
  - Are there “laws” that govern the structure and consequently the behavior of complex networks?
- Scientific, technological and societal implications

Scientific Implications – Fundamental Research Challenges

- Can a theory be developed to assess the vulnerabilities and fragilities inherent in complex networks to better understand their behaviors?
- To what extent does there exist a "network structure" that gives rise to the properties of large-scale, complex systems?
- Are there basic models with manageable set of parameters that can capture the basic properties of complex socio-technical systems?

How can this knowledge be used to design, organize, build, and manage complex socio-technical networks?

Classic Approaches to Modeling Real-World Networks

- Pure Graph Theory
  - The focus is on the combinatorial properties of artificial constructs
  - It is not concerned with the structure of human-made or naturally occurring networks
  - Limited relevance to real-world networks
- Applied Graph Theory
  - The approach is toward design and engineering
    - Not focused on understanding behaviors and dynamics

Classic approaches have tendency to overlook or oversimplify the relationship between the structural properties of a networked system and its behavior

Recent Approaches – Science of Networks

- The “new” and evolving “science of networks” is distinguished from classical approaches in three important ways:
  - By focusing on the properties of real-world networks, it is concerned with empirical as well as theoretical questions;
  - It frequently takes the view that networks are not static, but evolve in time according to various dynamical rules; and
  - It aims, ultimately at least, to understand networks not just as topological objects, but also as a framework upon which distributed dynamical systems are built.

Active Research in “Network Science”

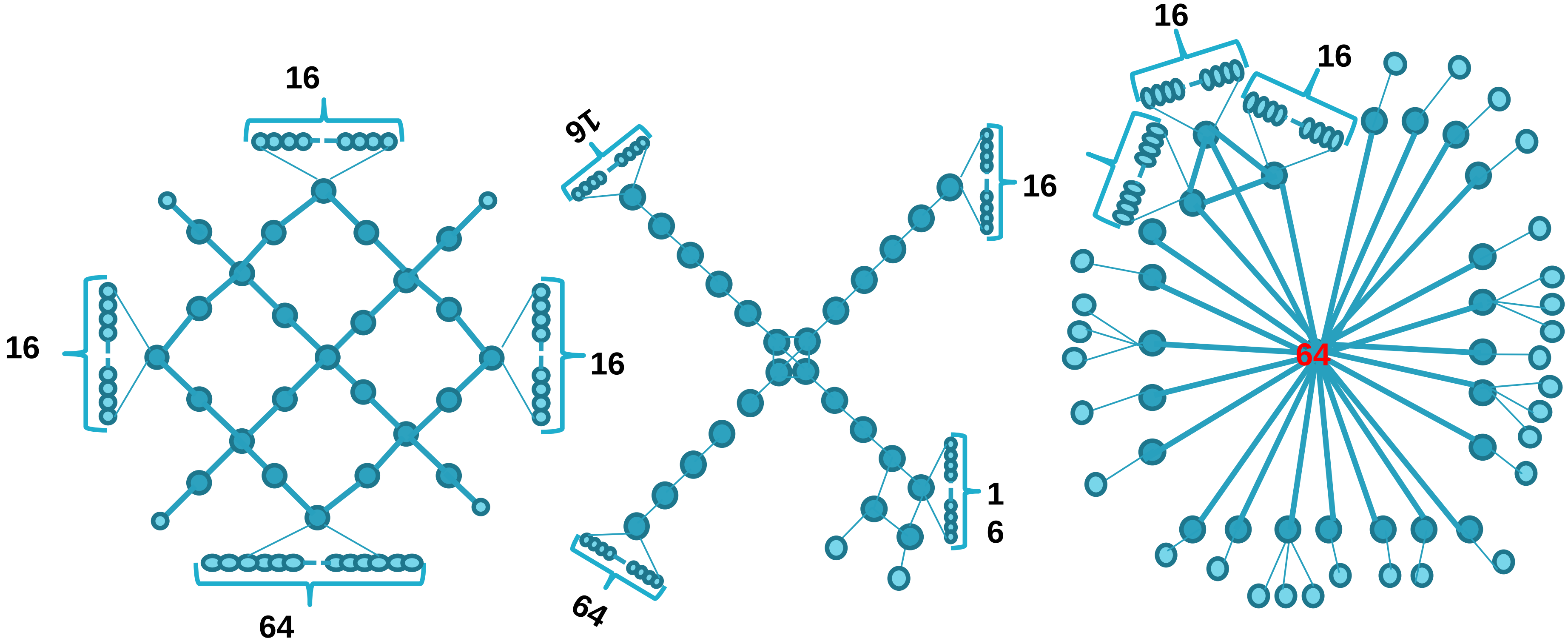
- Despite this stated focus on network dynamics beyond applied graph theory, much of the recent work seeks to characterize the connectivity of complex network systems.
  - Viewed as a graph, the focus is on studying the various properties of the network including its diameter, degree distributions, connected components and macroscopic structure
- Developing an understanding of the network graph leads to:
  - Understanding the “**sociology**” of content creation on the Web,
  - Analyzing the behavior of Web algorithms that make use of link information,
  - Distribution and evolution of **PageRank** values on graphs like the Web,
  - Predicting the **evolution** of Web structures and developing better algorithms for **discovering** and **organizing** these structures
  - Designing **crawl strategies**
  - Predicting the **emergence** of important new phenomena in the Web graph, etc

Power-Law Relationships of Internet Topology

- A number of descriptive models were developed attempt to characterize the structure and evolutionary dynamics of graphs, often with random graphs as the underlying null hypothesis for comparison.
  - Power laws have received particular emphasis in this context
- The large tail of the power law decays much more slowly than the tail of a Poisson Process
  - As a result, there is a small but significant number of vertices in the network with very high degree
    - They are called “central hubs” and represent the “Achilles' Heel” of the Internet

Power Law Distribution

Parsimonious Characterization



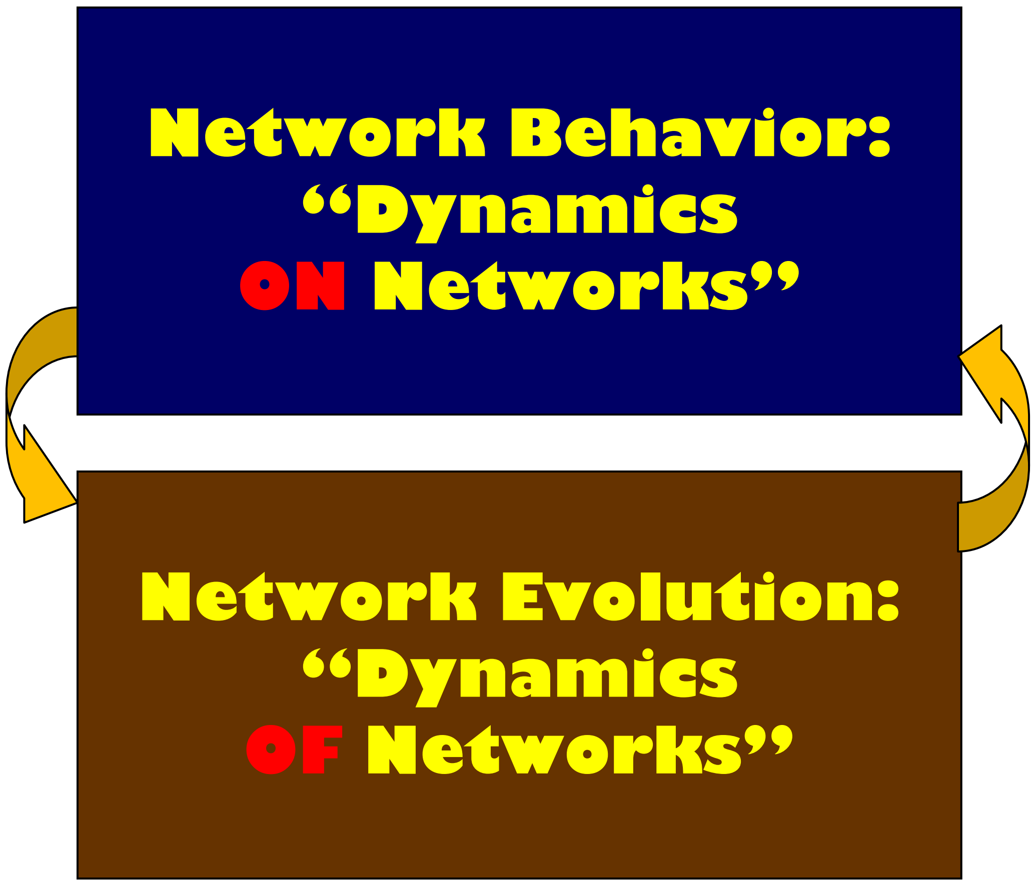
➢**Graphs having the *same power-law node* degree distribution parameters exhibit completely different "behavior" when measured against other performance metrics.**

➢**Similarity of Power Law degree distribution does NOT necessarily imply a network structure qualitatively similar [Alderson etal]**

Moral of the Story!

- Many statistical descriptions do not necessarily **uniquely** characterize the system of interest,
  - As such, there often exists considerable diversity among graphs that share particular statistical feature.
- Many processes can generate similar graphs
  - Little can be inferred about the underlying processes that caused an observed feature.
- Reducing a complex network to a simple graph may lead to the elimination of all of the key features that differentiate one system from another.
  - Ignoring the Internet heterogeneous components, layered architecture and feedback dynamics can lead to serious misinterpretation of observed graph structure

Models for Complex Socio-Technical Networks



Architectural Implications

- New “architectural thinking” to overcome fundamental limitations of current frameworks and design principles
  - Is the concept of layering fundamental, and if so what is the optimal set of layers appropriate for complex socio-technical networks?
  - How should functionalities be assigned to different layers
  - Is it time for cross-layering?
- Exploit new and yet to be discovered physical substrates
  - Leverage optical and wireless substrates for reliability and performance
  - Develop design principles for seamless mobility support
  - Develop architectures for self-evolving, robust, manageable

Layering as Optimization Decomposition*

- A computational way to view network design as solving a distributed optimization problem
- Computational problem is implicitly solved by the collective behavior of all the network elements
  - It enables a systematic study of protocols as distributed solutions to global optimization problems
  - It captures the inherent tradeoffs of protocol layering

*S. Low etal

LOD General Approach

- Understand each layer in isolation, assuming other layers are designed nearly optimally
- Understand interactions across layers
- Incorporate additional layers
- Ultimate goal – Entire protocol stack as solving one large optimization problem, where individual layers are "part solutions" of this problem

Formulation Example

Application Objective

Network objective

$$\max_{x \geq 0} \quad \sum_i U_i(x_i) + \sum_l V_l(w_l)$$

$$\text{subj to} \quad R(G)\, x \leq c(w, \mathbf{P})$$

$$x \in C(\mathbf{P})$$

IP: Optimize Route Given network Graph G

Link: maximize channel capacity given link resources *w and* desired error probability P

Rate: constrained by interaction of coding mechanism & ARQ

Layering Optimization Decomposition

Current Approaches	Layered Optimization Decomposition
❑ Descriptive Model	❑ Explanatory Models
❑ Describing a Layered Network Architecture	❑ Deriving Network Architecture from First Principles
❑ Piecemeal Solutions and Ad Hoc Layering	❑ Coherent, Consistent, Predictive Model

Architectural Implications

- Are current, inter- and Intra-Domain Routing Architectures adequate for future network?
  - Is the concept of “autonomous system” adequate in an environment where networks are built, operated and used by multiple stakeholders with a wide-range of self-interests that have to **compete** but yet **cooperate**?

Architectural Implications

- Are current, inter- and Intra-Domain Routing Architectures adequate for future network?
  - The concept of "**Autonomous Systems**", in an environment where networks are **built**, **operated** and **used** by multiple **stakeholders** with a wide-range of **self-interests**, leads to **conflicting routing policies** and potentially to **sub-optimal** performance
    - What other organizational structures have potential to lead to robust routing architectures future, socio-technical networks **?**
    - What frameworks must be developed to specify, analyze and enforce policies across competing stakeholders?
    - What impact new organizational structures on the relationship between routing, naming and addressing?
      - Should names have global meaning?

Socio-Economic Implications

- Enable new applications and new economies, while enhancing **usability**, ensuring **security** and **privacy,** and exploiting shared resource fully and fairly
  - Design secure, survivable, persistent systems, especially when under attack
  - Understand technical, economic and legal design trade-offs, and enable privacy protection
  - Explore AI-inspired and game-theoretic paradigms for resource and performance optimization

Powerful Concepts for a Paradigm Shift

- Virtualization
- Programmability, at all levels
- Federation
  - Three synergistic concepts that when combined have to potential to lead to a paradigm shift!

Physical Substrate ⟹ Virtual Substrates ⟹ Virtual Networks

From Bandwidth on Demand to Network on Demand!

Experimental Infrastructure for NetSE

- While we can create theories about complex networks and simulate our models, only through experimentation can we validate our theories
- Need for a shared infrastructure to support multiple experiments **simultaneously**, at **scale** and at different levels of **granularities**
  - Numbers and types of users, types of networks, numbers of nodes, geographical scope, …

Need for Collaboration

- Enable and promote collaboration and resource sharing across agency boundaries
  - Collaboration among PIs across different programs
    - What research challenges are already being explored and what research directions need additional R&D
  - Sharing of research infrastructure and testbeds
    - Exploit existing resources and avoid duplication of efforts
- International Collaboration

Concluding Remarks

- Our socio-technical networks of the future are too important to be left to chance or random developments
  - Network Science – Best way to predict the future is to invent it!
  - Need for a “Paradigm Shift”
  - True experimentation is needed.
    - Shared experimental infrastructure to enable, understanding, implementation and deployment of socio-technical networked systems of the future
  - Inter-agency and international collaboration

More Information

- Visit the CISE Web site at:
  - http://www.nsf.gov/dir/index.jsp?org=CISE
    - NetSE Cross-Cutting Program
    - Trustworthy Computing
    - CISE Infrastructure – CRI Program
- Visit the CRA CCC web site at:
  - http://www.cra.org/ccc

Thank You!

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