A Perspective on Research Directions In Network Science and Engineering

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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
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
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”.
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
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 et al]
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

Network Behavior: “Dynamics ON Networks”

Network Evolution: “Dynamics OF 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 networks
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 et al
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
Application Objective

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

subj to \[ R(G) x \leq c(w, P) \]

\[ x \in C(P) \]

Network objective

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

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<th>Current Approaches</th>
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<td>❑ Describing a Layered Network Architecture</td>
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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:
  - NetSE Cross-Cutting Program
  - Trustworthy Computing
  - CISE Infrastructure – CRI Program

- Visit the CRA CCC web site at:
  - http://www.cra.org/ccc
Thank You!