Tutorial Title: Exploring the Intersection of Theory and Engineering: Universal Laws, Architecture, and SDN

Speakers: John Doyle and David Meyer

Tutorial Summary:
The past twenty-five years have seen incredible progress in both the art and practice of network engineering, culminating recently in efforts such as Software Defined Networking (SDN) and the OpenDaylight Project (ODP). As this tutorial will explore, SDN both motivates and demands a much richer interplay between engineering, academic researchers, and mathematical foundations, something notably absent in networking. Perhaps not surprisingly, deep understanding of the principles and the associated theoretical framework underlying complex engineered networks (including the Internet, transportation and manufacturing networks, and many others) are just now coming into focus. Interestingly, one early observation is that these networks, while vastly different at the component level, exhibit astonishing levels of similarity at higher levels of organization. Further, it is not only engineered networks that exhibit these common architectural building blocks: both technological and biological networks share many of the same "universal architecture" features. (A caveat is "when they work," since both evolution and design can make catastrophic errors.) Also, SDN appears to be much closer to this architectural ideal than traditional architectures, which will be a central theme of this tutorial.

What can account for the astonishing universality of these architectural features and associated tradeoffs that we observe in complex systems, and can we find a theoretical framework that accounts for this convergence? Can understanding these fundamental and universal features of networks help us more efficiently build and operate networks such as the Internet? The goal of the nascent theoretical foundation is not only to explain and understand network systems such as the Internet but also understand both the successes and shortcomings of these systems. In fact, this growing theoretical framework identifies surprisingly familiar design components, in particular protocol-based architectures and layering, with reflect and reflex, virtualization and embodiment, as crucial ingredients for scalable and evolvable networking.

That said, while recent progress on the theoretical basis of network engineering has been significant, we still lack the kinds of principles, theory, and tools for networked systems that we find in other (and in many ways simpler) critical engineering disciplines. These systems have the general characteristic that unlike many of today's Internet control systems, they depend on sophisticated active control systems for stability, scalability and evolvability. Interestingly, modern software control systems enabled by SDN have the potential to shift traditional Internet control paradigms to similar active control regimes and as such, SDN itself brings into focus the urgent need for a more complete general theory of complex engineered systems. However, most if not all of the machinery that underlies such a general theory is for the most part foreign (if not alien) to the network engineering community. Further, "compilation" of these concepts, where they exist, into forms consumable by the engineering community is close to non-existent.

Hence the advent of SDN (and more generally, multi-scale software-based network control) represents a unique and significant opportunity to build much needed bridges between the theory and engineering communities. In fact, since theorists require the insight and real world experience of the engineering community to build relevant theoretical frameworks and engineers need the tools and understanding that theorists seek in order build scalable and understandable networks, building bridges between these communities is a core goal of this tutorial. Since most Sigcomm attendees are "researchers" that sit between theory (mostly CS and modestly related to networks) and engineering, SIGCOMM provides an ideal opportunity to explore the potential and limits of available theory from both an engineering and a mathematical perspective.

To this end this tutorial covers a range of related topics from a review of control theory, computational complexity, optimization, and statistics (including various mashups in Machine Learning, AI, and "big data" and their relevance to SDN), new developments in information theory

such as network coding, and the role of formal methods in embedded system, as well as their application to modern engineering problems and approaches. Many of these principles will be illustrated using concrete use-cases from Internet engineering (as well as other disciplines such as biology and neuroscience), and the tutorial is designed to be highly interactive. Finally, we pose several important questions: First, what are universal laws (tradeoffs) that put fundamental bounds on what engineers can build, and second, are there intuitive every-day "use cases" that demonstrate these tradeoffs? Finally, can we use these laws to better understand the complex networks we observe (whether technological or biological), and perhaps equally important, how can we use this new understanding to build new engineering systems which help us to design, build, and operate these networks?

Finally, as a logistical point, we would like to avoid scheduling conflicts with HotSDN as many will want to attend both HotSDN and this tutorial, so with the current schedule, the tutorial should be on Friday.

Tutorial Outline (Table of Contents):

1. Introduction: Framing the Discussion
    1. SDN and the TCP/IP architecture: past and futures, differences and similarities
    2. Developing common terminology
    3. New uses of the network and their implications
    4. How network engineers can benefit from breakthroughs in network theory
    5. Past theory, particularly "layering as optimization" and relevance to SDN
2. State of the Art in Network Theory
    1. Review: Theory in Control, Computing, Information, and Physics
    2. Universal laws and their unification
    3. Network control challenges
    4. What theory has been pursued to date in networking?
    5. What new systems and theory are relevant to SDN and the future?
    6. What are current holes that need closing
    7. What are fundamental limits to theory itself in this domain
    8. Why "Network Science" is bad networks and bad science
3. Network Architecture
    1. Universal architectures
    2. Layering in technology, biology, and societies (animal and human)
    3. Constraints that Deconstrain
    4. Reflex and reflect versus SDN control and forwarding planes
    5. Virtualization and embodiment in layered architectures
    6. Complexity, Robustness, and Fragility
    7. Evolvability, Scalability, Verifiability
    8. Relationship between robustness to component and environmental uncertainty versus security against malicious, intelligent adversaries
4. SDN: Mapping Theory to Architecture
    1. SDN "Hypothesis" and wrong turns
    2. SDN as a 3-layer architecture
    3. Horizontal Application Transfer and SDN
5. Moving Forward
    1. What theory is required, and what is missing?
    2. What will be the impact of new applications on conventional and SDN networks?
    3. Is there a role for SIGCOMM in connecting theory to practice?
6. Discussion

Type of Tutorial: "Interactive" Lecture

References to previous iterations of the tutorial:
http://conferences.sigcomm.org/sigcomm/2003/tutorial2.html was related in that it explored some specific aspects of networking and relevant theory. This proposed tutorial is taking advantage of both the much expanded architecture thinking around SDN, and broader theory developments in the last decade, particularly in related subjects in technology and science.

Requirements for the tutorial room: Ability to project from laptop, power for laptops

Expected Audience and Prerequisites:
This tutorial is intended for those who are interested in exploring the state of the art in the theoretical underpinnings of complex, highly engineered systems (such as the Internet) and how this understanding can be applied to the design and engineering problems embodied in new control architectures such as SDN. Basic understanding of the Internet architecture and SDN is required. In addition, understanding of basic concepts from CS mathematics, control theory, and communication theory, as well as trends in algorithms for “big data” would be helpful but is not required.

While this tutorial will not present new results, but integrate and organize existing ideas about SDN and diverse theory, almost all of the latter will be new to most Sigcomm attendees. This will make it a unique and challenging tutorial, at least as far as we can tell. The program committee members who are most familiar with this material, and perhaps could assist in evaluating its suitability, are Paul Barford and John Wroclawski. Doyle also did the above mentioned and somewhat theoretically oriented 2003 workshop and co-authored the 2004 student prize paper with Walter Willinger, and has not worked with him recently, but Walter is also familiar with the general themes of the tutorial.

Biographies:
The two organizers (Doyle and Meyer) are at the fringe of the Sigcomm community, and arguably at opposite extremes. They both bring unique perspectives to SDN and the role of theory. They hope to give all the lectures themselves but will bring in additional experts if they cannot do justice to some important topic.

John C. Doyle is the Chameau Professor of Control and Dynamical Systems, Bioengineering, and Electrical Engineering at Caltech. He has a BS and MS in EE, from MIT, 1977 and a PhD in mathematics, UC-Berkeley, 1984. His current research interests are in theoretical foundations for complex networks in engineering and biology, as well as multiscale physics and financial markets, focusing on the interplay between robustness, feedback, control, dynamical systems, computation, communications, and statistical physics. Prize papers include the IEEE Baker (also ranked in the top 10 "most important" papers world-wide in pure and applied mathematics from 1981-1993), the IEEE AC Transactions Axelby (twice), and the AACC Schuck. Individual awards include the IEEE Control Systems Field Award (2004) and Centennial Outstanding Young Engineer (1981), the IEEE Hickernell (1977), AACC Eckman (1983), and UCB Friedman (1984). He has held national and world records and championships in various sports.

David Meyer is CTO and Chief Scientist at Brocade Communications, as well as being the Director of the Advanced Network Technology Center at the University of Oregon and a Senior Research Scientist in the Department of Computer Science at University of Oregon. In addition, he is currently the chair of the SDN Research Group (SDNRG) in the IRTF and is the chair of the Technical Steering Committee of the OpenDaylight Project. He holds a MS in Computer Science from the University of Oregon. His current research interests include Software Defined Networking, Systems Biology, Control and Complexity Theory, and Nano-scale networking, among others.