Research Statement
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I am interested in designing, building, applying, and analyzing networked systems at many scales, in many contexts, and doing so leveraging knowledge from disparate fields of research. I see networked systems as the enabler of profound changes in virtually all areas of global society, and aim to develop novel technical solutions to meet the unarticulated challenges brought about by new societal needs.

My work focuses on three core questions:

- Architecture: how do we design elegant, efficient, and scalable systems?
- Operation: how do we effectively analyze, understand, and manage systems?
- Application: how can we apply systems to real problems, and what is their impact?

I ask these questions across a wide range of systems and seek to articulate and address entirely novel research questions or seek to challenge conventional wisdom on existing topics. I develop research questions from careful observation of real world challenges, often motivated by the potential for broad-based societal impact. As appropriate for the problem at hand, I am as at home with careful engineering of low-level system details, at one extreme, as with abstract reasoning about principles of the Internet’s architecture at the other. I enjoy collaborating not only across an array of sub-disciplines of computer science (including with researchers in networking, distributed systems, cryptography, human-computer interaction, sustainable computing, and ICTD), but also with researchers outside of computer science (including agroecology, economics, and public policy), as I find that such collaborations bring to the fore diverse problem-solving approaches that are needed to tackle the hardest research questions.

Prior Work

Architecture

My research on architectural questions has involved work on specific aspects of networked systems as well as the reexamination of whole architectures.

My work to develop and analyze new network architectures has been with the recognition that the demands on the Internet today far exceed its original design and that of classic protocols [CCR '11, HotNets '11a/b, HotNets '12, SIGCOMM '16, CCR '16]. The broad aim of this work is to identify and eliminate barriers – undesirable coupling of systems, conflation of policy and mechanism, and inflexible interfaces – to the evolution of network architecture. In this work, we focused on evolution as a key enabler of long-term architectural innovation: an Internet with many seamlessly coincident protocols and designs is one in which better protocols can emerge without converging to technological lock-in. We made network evolution possible by decoupling network applications from the specifics of the protocol stack, decoupling hosts and local domains from a single global network architecture, and decoupling domains from each other via a layer of indirection in all interdomain packets.

A number of my projects have involved the design of new techniques for network congestion control and resource allocation [HotNets '06, SIGCOMM '07, NSDI '10, SIGCOMM '13]. One common theme in this congestion-control work is the re-examination of the assumed tradeoff between per-flow efficiency and inter-flow fairness. Contrary to conventional wisdom, we found that it was possible to achieve near-ideal
network efficiency while increasing the offered load on the network, without sacrificing fairness, by judiciously introducing redundancy. In the context of resource allocation, our key observation was that we can use existing congestion-responsive network traffic to perform inference for us, thereby providing an estimate about a fair and efficient allocation of bandwidth and the potential for reallocation of traffic across paths.

A distinct but inter-related thread of my work focuses on security: security both as an enabler in networked systems, specifically in the context of routing [SIGCOMM '04, ICALP '05, CCR '07, ToN '09, HotOS '15], and as an end in itself [PETS '09, ICN '11, Consulting]. I have sought to develop and analyze mechanisms for secure and authenticated network routing; in this work, we developed efficient mechanisms to cryptographically authenticate routes through the network while enabling the delegation of authentication tokens that govern traffic accounting and access. I have also sought to directly improve network security and privacy, such as in my many years of consulting work with Bruce Schneier on security analyses of commercial systems.

**Operation**

More recently, I have increased my focus on operational challenges with the recognition that some of the key unsolved issues in networked systems – as their scale and complexity grows dramatically – relate to our ability to analyze, understand, and manage them. My research in this direction has taken two primary forms: 1) on debugging and testing [USENIX '13, SIGCOMM '14] and 2) on management and operation [DEV '15, Google].

Given its role today as key infrastructure for global society, it is crucial that we can identify flaws in network protocols and larger networked systems early in the process, before the problems manifest in production environments. For the former, we developed a tool for directly testing network stack behavior in a manner akin to unit testing, but with live network stacks. This enabled us to identify key bugs in the Linux kernel’s network stack and to develop a regression test suite that could be run by developers against an unmodified kernel. For the latter, we developed a system for rapidly identifying the minimal causal sequence of inputs that triggers an exception in a distributed controller of a software-defined network (SDN), enabling the identification of key bugs in several open source and proprietary controllers.

Management and operation of networks has received less attention from the research community in part because addressing these challenges requires deep practical experience with and access to the networks in question. Over the last several years I have been working to develop new approaches to managing networks in challenging environments. My expertise in this regard was amplified during my time at Google where I worked to develop the next-generation SDN controller for Google’s networks. A specific interest of mine has been the expansion of universal Internet access, a challenge that often requires the deployment of rural Wireless ISP (WISP) networks. I led a team to build a WISP deployment – still operating today providing broadband to a previously unconnected region in a remote area of California – thereby having a testbed to explore and develop new management systems for WISP operations, which typically are poor in resources and expertise.

**Application**

I have sought not only to apply a systems approach widely, but also to contribute to the understanding of the concrete and abstract impact of networked systems in broader contexts, especially those motivated by ecological sustainability and economic development. Ultimately I see my work on the questions above – about architecture and operation – as short-term building blocks on a longer time horizon, with larger societal objectives in mind. Thus I seek challenges that leverage my understanding of networked systems in their application to societal challenges.
A key challenge in the nascent field of computing for sustainability is that of analysis – disambiguating problems and identifying opportunities for true impact [HotNets ’11, NordiCHI ’14, iConference ’15, LIMITS ’16]. My analysis work to this end has examined the energy and ecological impact of the Internet, identifying the material footprint of networks as a key sustainability challenge that had been neglected in past research. Other work examined types of research in sustainable computing, in which we identified principles for future research in the field, rooting the area in a firm foundation of research from ecology and ecological economics.

In addition to analysis, I have worked to propose new designs for networked systems in challenging contexts [E-Energy ’12, alt CHI ’16, DEV ’15, HotNets ’16]. For example, our initial work on computational agroecology identifies the key potential role of computing in enabling the advancement of the field of agroeconomics, which is the science and practice of applying ecological theory to achieve a truly-sustainable system of agriculture. In doing so, we identified the enormous potential societal impact of our techniques to apply scale-out thinking from computing in agriculture through agroecology rather than more conventional practices.

My research in the areas of computing for sustainability and economic development has appeared in a wide range of venues in large part because the fields are young and diverse. Due to strong interdisciplinary interest in these topics, I co-founded a new workshop, ACM LIMITS, which is now headed into its third year and is beginning to impact research in other sub-disciplines of computer science such as HCI and ICTD.

Current and Future Research Directions

**Scalable Architectures for Network Function Virtualization.** Increasingly carriers and datacenter operators alike are moving all network packet processing to general-purpose software-based forwarding pipelines. Some of the key architectural questions that remain for Network Function Virtualization (NFV) relate to the placement of network processing functionality – in a hypervisor, a kernel, a container, a user-space daemon, an application, or even a smart switch. We are examining whether there are general design choices that apply to a wide range of applications and workloads, and whether there are system designs that enable seamless use of the same flexible NFV framework across all such use cases. In addition, there is a key challenge of presenting indistinguishable behavior when executing NFs regardless of how the framework chooses to implement them; this decoupling enables adaptation to changing workloads and diverse hardware, enables scaling based upon real-time analysis of network traffic, and enables the evolution of applications independent of the NFV framework.

**Decentralized Censorship-resistant Networked Systems.** In recent years, authoritarian regimes have imposed partial and total network blackouts during times of civil strife and political upheaval, and have used heavily-surveilled network applications to disrupt democratic movements. I have ongoing and planned future work to address two different dimensions of this challenge. The first involves circumventing total network blackouts via a decentralized mesh network of smartphones; the key challenge in this domain is in addressing the seemingly-fundamental tradeoff between user anonymity and the network’s resilience to Sybil attacks, spam, and jamming. We have developed a novel protocol leveraging lightweight secure multiparty computation to use a private social graph to prioritize messages. The second involves a distributed application infrastructure for use in highly-surveilled (but non-blackout) conditions; this infrastructure is designed to circumvent censorship and surveillance while yet again ensuring in such a decentralized environment the ability to perform distributed filtering. Moderation is key to all cloud-based web services and is typically provided by centralized operators, but in this context we cannot rely upon an impartial centralized moderator. However, a decentralized service infrastructure without means to filter can quickly become unusable due to misbehavior. We are developing a new mechanism, fork moderation, to balance these two key
needs, in which a distributed data stream can be efficiently and securely cloned at a specific point in time, edited, and republished, recursively so, and are developing interfaces to enable the seamless development of systems that build upon this mechanism.

**Automated Rural Network Design.** In prior work I analyzed the challenges of expanding network connectivity to disconnected communities and developed management systems to aid in operating networks in such challenging contexts. However my prior work did not address a key unsolved challenge, that of planning such networks, which is difficult for a team of experienced networking engineers and researchers let alone the average rural network operator with no prior expertise. As a result, in ongoing and planned future work we are building a system to enable the automated planning of such frontier networks. To address this challenge requires not only deep domain expertise and experience building such networks, as I have developed over the past several years, but also new techniques to grapple with the combinatorial explosion that occurs when performing joint-site planning – selecting the best handful of sites across rough terrain that together meet a complex array of criteria. This planning challenge is exacerbated by another system we are developing in this context to simultaneously reduce the cost of a WISP network while dramatically increasing its performance and reliability. Using an analogy to RAID, we are developing a protocol called RAIL – Redundant Arrays of Inexpensive Links – which allows for the flexible, fine-grained tradeoff of increased performance, increased reliability, or a combination of the two by replacing expensive monolithic backhaul links with cheaper, smaller links and a new multipath protocol. Our initial analysis suggests the potential for a network planned with our system and using RAIL to deliver over five times the network capacity for the same cost as today's network designs.

**Computational Agroecology.** One of the greatest ecological challenges global society faces today stems from agriculture, which, among other impacts, is currently responsible for more carbon emissions globally than any other sector. However many sustainable alternatives sacrifice yield and increase cost, minimizing adoption. The science of agroecology, developed in recent decades, has identified new ecologically-based models and practices that have the potential to sustainably deliver high yields at low cost by emulating natural ecosystems. However the field is young and implementation of the science is extraordinarily complex, hindering adoption. We have recently presented a vision of the challenges in the use of computing to enable the implementation and scaling of agroecology. To deliver on this vision, we aim to explore key research questions about how computing can aid in conceptualizing, designing, building, managing, and harvesting agroecosystems: systems that understand complex natural interactions, the requirements and context of the agroecosystem in question, and interface with the people and machines involved in practice. This highly interdisciplinary work will require the development of new techniques from networking to crowdsourcing to data modeling to robotics. This new area we are developing has significant potential for novel networked systems research in the context of multi-layered, complex natural systems.