Statement of Research Interests, Brad Karp

My research experience has spanned high-speed switch design; efficient host operating system support for high-speed network interfaces; collaboration in implementation of one of the first Mobile IP systems; and design, building, and deployment of a mobile, wireless network routing system. Networking systems interest me broadly. But today, wireless and mobile networks hold my interest most, because that specialization affords the opportunity to play more of a role in defining new problems than do longer-established areas of networking.

My approach in choosing problems is to examine assumptions in present-day systems and evaluate their scaling properties, to discover undesirable limitations. I seek to design novel, more scalable, more robust network systems that perform well where today’s cannot. When solving a problem I look to apply new technologies that enable new algorithmic approaches; theoretical constructs as-yet unapplied to a problem; and a careful questioning of which precepts in prior designs are well-founded.

In my thesis work at Harvard and ACIRI (now named ICIR) in Berkeley, I created and evaluated a novel routing algorithm and protocol, Greedy Perimeter Stateless Routing (GPSR), for mobile, wireless networks. The fundamental scaling challenge for a routing system is to find correct routes on networks with many nodes, even when the network topology changes, without generating an excessive network load of routing protocol messages. Large-scale, mobile networks represent an extreme point in this scaling challenge: their topologies change rapidly, they involve large populations of nodes, and they often consist of nodes with impoverished memory and network capacity resources. Previously proposed routing systems do not scale in such environments. A truly scalable solution to the mobile routing problem will enable such novel applications as sensor networks, metropolitan-area rooftop networks (in which citizens form self-managed, peer-to-peer networks using radios they own and operate), and ad hoc networks.

The central idea in GPSR is to route geographically, using the positions of nodes in a network to make decisions about how to forward packets to a destination. New technologies enable network nodes to learn their positions. Position information allows consideration of the routing problem in a different algorithmic framework; prior routing systems exchange information concerning the the global network topology, and their scaling limitations stem from that common root. I first investigated the behavior of a simple greedy geographic forwarding algorithm. Analysis of its failure modes led me to discover that it is voids, empty regions in a topology where no nodes are situated, that cause greedy forwarding failure. I developed an algorithm for circumnavigating these voids, to recover where greedy forwarding is impossible. The circumnavigation strategy, perimeter routing, makes use of a novel application of two planar graphs, the Relative Neighborhood Graph and the Gabriel Graph. These constructs were long known to computational geometers, but had not previously been applied to network routing. The resulting system can route to any connected destination on any wireless network topology. The scaling behavior GPSR achieves derives from the minimal state the algorithm requires: each router needs to know only the positions of its immediate neighbors. Small state confers two benefits: the memory resources required at a node for routing are minimal, and independent of the number of network destinations; and the communication cost required to find up-to-date routes is minimal, and only involves propagation of state a single hop. Yet the routes found by GPSR are most often equal in length to shortest paths. These properties allow GPSR to perform well on large-scale mobile networks, where previous routing systems...
I rigorously evaluated GPSR in simulations that model the complete capacity and contention behavior of IEEE 802.11 wireless networks, commonly used by consumers today. This evaluation led to many enhancements to the GPSR protocol to improve its interactions with real radios, and the final system offers significantly greater performance and robustness than do previously published routing protocols.

More recently, in my post-graduation year at ICIR, I have worked with a student advisee, Ming Zhang, to create an enhanced version of the TCP protocol that is robust on networks that deliver packets in an order different from that in which they are sent. This work seeks to end a severe restriction in the design of today’s Internet: it is utterly taboo to deploy new systems that cause packet reordering, because the performance of TCP, the protocol that carries most Internet traffic, plummets when packets arrive at the receiver out-of-order. Reordering is perceived as a malfunction, as is the case with widely known Internet measurements that show some paths persistently reorder packets; or as an indication that a link technology is maladapted for use with TCP, as with satellite links that introduce reordering. But the most compelling reasons to improve TCP’s robustness to reordering are the beneficial systems that cannot be built, because they would introduce reordering. Multi-path routing, for example, improves the throughput a connection attains by spreading its data across multiple paths, but is undeployable in today’s Internet because it reorders packets.

We developed a control loop for adapting TCP’s loss determination method dynamically, based on measurements the sender takes of the reordering behavior of the network. The result is a TCP with significantly enhanced throughput on reordering paths, demonstrated in simulations. Its deployment could substantially loosen the in-order delivery restriction on the Internet architecture. In evaluating this work, we address fundamental problems in sending data on a network that reorders data: trading off delivery delay vs. effective data transfer rate, and trading off marginally slower adaptation to network congestion vs. improved data transfer rates on reordering paths.

Looking ahead after ICIR, I am excited to lead a group in pursuing my research agenda. I plan to design, build, and deploy a rooftop network. This project will combine my interests in wireless networking and novel network architectures. It will advance the state of the art in deployed scalable wireless systems, and has great potential for positive societal impact. In a rooftop network, citizens form a metropolitan-area network, using radio hardware they own and operate. Here, the user’s radio is both his access device, and forwards traffic for other users in the network. Today, every user who wants Internet access pays a service fee to a network service provider to have his home connected. The users of a rooftop network cooperate to form a shared network infrastructure, and can share fewer connections to a network service provider. Effectively, this architecture replaces the edge of the service provider’s network, which today aggregates separate connections to every house, with customer-operated radios. Community wireless “users’ groups” have sprung up in cities including San Francisco, Seattle, London, and Cambridge, MA, comprised of hobbyists with 802.11 wireless radios who want to form networks with one another. But they lack sufficiently scalable and robust network software systems to achieve their goals.

The challenges of creating such a network are manifold. Many nodes will participate, so the routing system must scale well. The topology will be dynamic, as users are free to power nodes on and off, so the routing system must be responsive to topological changes in the network. Users are unlikely to be skilled network administrators, so little to no configuration at network nodes should
be required. The limited capacity of wireless media presents challenges in traffic engineering; routing flows in a way to minimize the congestion created by their competition for radio bandwidth will significantly improve the data transfer rates users experience. I believe that my prior work poises me to build a novel rooftop networking system that addresses these challenges.

Geographic information will enable scalable rooftop networks. The rooftop application was part of the motivation for GPSR’s design, and I look forward to deploying GPSR in this context. Deployment experience with GPSR will undoubtedly yield further improvements to the algorithm and protocol—and such experience offers the most rigorous evaluation of a system’s true worth. GPSR provides a natural framework for routing competing traffic flows in a dispersed fashion, without knowledge of the end-to-end network topology. I’ve begun building a geographic traffic engineering system atop GPSR with two students.

Multi-path routing will be useful on wireless rooftop networks and the wired Internet alike. Sending data over multiple network paths will in many cases increase the data transfer rate a single connection experiences. Using such a system with most Internet applications has been impossible until the advent of a reordering-robust TCP. By building deployable implementations of multi-path routing and reordering-robust TCP, I aim to demonstrate concretely the additional utility offered by network systems that reorder packets.

I look forward to addressing the many challenges in these research endeavors, and to the continuing intellectual rewards of building systems. In my career thus far, I have derived immense satisfaction from the opportunity networking research provides for marrying the theoretical and practical; algorithmic thinking and system building. Designing new algorithms and systems with fundamentally sound scaling properties offers the joy of completely solving a puzzle. Demonstrating these systems’ worth experimentally, to show that a design that looks sound in the abstract is also well suited to use on real networks, offers the joy of seeing an idea made reality. I am eager to share these challenges, the tools for addressing them, and the rewards of a career in robust, scalable system design with my students.