Research Statement - Sanjay Rao

My research interests are in networking. In my research, I seek to tackle real world problems, while adopting a style that strikes a balance between systems building, and addressing conceptual and scientific issues. I view the development of real infrastructure/systems/applications as essential for establishing the credibility of a research direction and to ensure that the right questions are being tackled.

My thesis work exemplifies the style of research I am interested in pursuing. My thesis has been motivated by the real world challenge of enabling the "ubiquitous deployment" of bandwidth-demanding group communication applications such as conferencing and broadcasting on the Internet. My research forms a key component of, and has been validated by, a full-fledged operational broadcasting system that is proving a valuable tool to the community. The designs have evolved through experience with prototypes deployed in the real world, and the experience has led me to important design insights that have been overlooked by the community.

Thesis Research:

My thesis research has been conducted in the context of *End System Multicast (ESM),* a project that I initiated at Carnegie Mellon along with my colleague Yang-hua Chu, and have played a leadership role in. For much of the 1990's, researchers attempted to enable deployment of broadcasting and conferencing applications using the IP Multicast architecture. In spite of intense efforts for over a decade by both the research and the industrial community, the deployment of IP Multicast has remained extremely limited. The ESM Project has been exploring an alternate architecture for supporting these applications, where all multicast functionality is supported at the application layer, and there is no router level support.

My thesis provides the intellectual foundations of the ESM project and makes contributions at the architecture level and the design level. The research forms a key component of a broadcasting system that we have built based on End System Multicast. This system has been operational for over a year, and has been used to broadcast over 15 events which include conferences such as Sigcomm 2002, Sigcomm 2003 and SOSP 2003. The system has been used by over three thousand people spread over four continents, in commercial, educational and home settings, and behind NATs and firewalls. Our attempts to deploy prototypes among real users represent a fairly unique effort in the overlay research community, and demonstrates the deployment potential of the ESM architecture.

At the architecture level, my work with Yang-hua demonstrates using simulations, Internet experiments and live deployment, that the benefits of an End System Multicast architecture outweigh the performance penalties involved. Our initial arguments for End System Multicast appeared in *Sigmetrics 2000,* which was the first published paper that proposed and evaluated an overlay/application level multicast solution to my knowledge. Overlay Multicast has since evolved into a full-fledged research area, and the Sigmetrics paper is regarded as an influential work that has generated significant follow-up efforts. Some of the metrics it introduced such as *Stress* and *Relative Delay Penalty* have become standard metrics for measuring the performance of an overlay.

At the design level, my research addresses a key challenge with End System Multicast - the design of protocols that construct efficient overlay networks among participating end systems in a self-organizing and self-improving fashion. The scale of nodes involved, the dynamics of participation (group dynamics and Internet congestion), and the heterogeneity in the Internet (diversity of nodes and diversity of bandwidth and Internet path characteristics) make the design of these protocols very different than traditional distributed algorithms. I led the design and implementation of *Narada,* one of the first self-organizing overlay protocols, which was primarily targeted at multi-source applications such as audio and video conferencing. I was also responsible for the design and implementation of the self-organizing protocol used in our operational broadcasting system, and led efforts to build tools and methodology to analyze its performance.

The distinguishing aspect of my research is that the protocol designs have evolved through extensive experimentation and experience with overlay prototypes in the real world. The unique approach has led me to explore important issues that have been overlooked by the community, and to key insights that are applicable to any protocol. I played a lead role in an Internet evaluation of overlay protocols which identified that it is critical for a self-organizing protocol to dynamically adapt to network metrics such as bandwidth and latency, and further when simple heuristics to this end were incorporated, the performance benefits were significant (Sigcomm 2001). My subsequent experience has indicated that a fundamental parameter in such adaptation is the time taken to detect poor application performance, and this parameter must be dynamically tuned depending on various factors including the network connectivity at the client and the resources available in the system. I played an active role in a study where we identified that given the adaptive nature of the application, simple probing techniques such as round trip time and bottleneck bandwidth are quite effective in guiding parent selection (Infocom 2003). My recent experience has indicated that heterogeneity among nodes is one of the predominant features of real Internet environments today, and it is critical to incorporate heuristics in a self-organizing protocol that differentially treat nodes based on their capabilities.

Future Directions:
The Internet today is dominated by applications such as the *world wide web,* that are based on the client-server model of communication, and *e-mail,* which primarily enable asynchronous communication. I am motivated to work towards creating the next generation Internet where large scale distributed applications, particularly those that enable a greater degree of synchronous communication are common-place. I view my thesis efforts as a first step in a longer journey, and plan to investigate a broad set of issues with overlays as an important means towards realizing the longer term goals. First, I would like to explore the interplay between applications, overlay architectures, and protocol design. For example, should applications be deployed at actual end-points, or as part of dedicated infrastructure, or using a wide range of possible hybrid architectures ? What kind of support must an infrastructure provide to individual applications? How sensitive is the design of overlay protocols to the particular architectural choice? A second direction I see as critical is the development of new intellectual frameworks, foundations and simulation methodologies that can help scientifically analyze and compare overlay designs. Overlay design today is dominated by ad-hoc heuristics and design elements. To a large extent, the ad-hoc nature of designs is unavoidable given the complexity and unpredictability of the Internet, and the nature of individual applications. However as a result, it is difficult to make confident assertions about the properties (for example, robustness or scalability) of a design. An associated challenge is developing simulation models at an appropriate level of realism - while current simulators are often too far removed from reality and can potentially mislead, it is next to impossible to model all the complexity inherent in the Internet. A third direction of a much longer term nature involves revisiting fundamental aspects of the Internet architecture, given that a substantial deployment of overlay applications may impact the Internet in ways that we poorly understand today.

Concurrent with my interest in overlays, I would like to initiate research on **self-managing systems,** an area that I believe is going to gain in importance in the coming years. Research in computer systems and networks has over the last several decades emphasized design for performance. However, over the years, systems have become complex, and the cost of managing and maintaining systems is proving an equally important if not greater challenge. These issues appear across a wide spectrum of systems. On the one hand, naive and unsophisticated users increasingly need to handle a greater number of devices with the trend towards multiple computers per home, and the growth of home networking and pervasive computing devices. Apart from the time and effort involved, poor management, such as the failure to download software patches in a timely fashion, can prove a source of security vulnerabilities. On the other hand, large organizations such as ISPs and data hosting centers expend a lot of resources in keeping systems up and running, and frequently need to deal with problems arising from error-prone manual configurations. Finally, the emergence of distributed and shared overlay infrastructures (e.g. Planetlab) leads to important issues regarding how they must be managed. All these trends lead me to believe that there is need to address issues related to the management of systems in a well thought out and systematic fashion, and I believe this is going to be an important long term direction in the coming years. I also believe that a key challenge in pursuing this research is the need for fundamentally new evaluation methodologies, potentially involving interdisciplinary work with HCI researchers.