Network Science and Engineering: Developing a Comprehensive Strategy

Is there a science for understanding the complexity of our networks so that we can engineer them to have predictable (or adaptable) behavior? In response to this fundamental research challenge, the NSF Directorate for Computer and Information Science and Engineering (CISE) and the research community are developing a comprehensive strategy to advance research and education in Network Science and Engineering.

The call to arms is to understand networks broadly and at multiple layers of abstraction from the physical substrates through the architecture and protocols to networks of people, organizations, and societies. The intellectual space surrounding this challenge is highly interdisciplinary, ranging from new research in network and distributed system design to the theoretical underpinnings of network science, network policy and economics, societal values, and the dynamic interactions of the physical and social spheres with communications networks. Such research holds great promise for new knowledge about the structure, behavior, and dynamics of our most complex systems -- networks of networks -- with potentially huge social and economic impact.

The Network Science and Engineering (NetSE) Council is composed of representatives from multiple network science and engineering research communities and is providing the scientific leadership to develop a compelling research and education agenda to meet this challenge, including its inter-related theoretical, experimental and societal aspects. This agenda identifies a core set of fundamental research questions and drives a set of experiments to validate theories and models, which in turn will define requirements for any infrastructure, facilities and other resources needed to support Network Science and Engineering research.

The NetSE Council membership reflects these deep linkages to theory, economics, social policy, and emerging fields of computer science and is now engaging the research communities in organizing a series of workshops that will inform the evolving research agenda.

To augment the considerable prior effort to define research challenges in networking and distributed systems, NetSE workshops are being planned in the following areas:

- **Network Science –** what are the new mathematical tools and techniques that can provide a scientific basis for network understanding that informs future network design? This workshop is being co-organized by John Wroclawski and John Doyle.

- **Network Economics –** what are the models and theories that underpin economic decision making, by individuals and organizations, in networked environments? This workshop is being co-organized by Mike Kearns and Colin Camerer.

- **Network Design and Societal Values –** how do (and how should) network designs reflect societal values? This workshop is being co-organized by David Clark and Helen Nissenbaum.

Along with these workshops, small focused groups will meet to extract and build upon prior efforts in the following areas:

- **Theory of Networked Computation –** what are the algorithmic and complexity questions associated with computing in and on a network?

- **Network and Distributed Systems Architecture and Engineering –** what are the architectures, services and protocols that form the basis for better future networks?

The output of these workshops will be used, along with relevant prior efforts, to synthesize a broad and comprehensive NetSE research and education agenda. The first draft of that agenda will be available for community review and comment in Fall 2008.

As a concurrent activity, community planning for the suite of infrastructure that will support NetSE experiments has been underway since 2005. This suite is termed the Global Environment for Network Innovations (GENI). Although its specific requirements will evolve in response to the evolving NetSE research agenda, the facility's conceptual design is now clear enough to support a first spiral of planning and prototyping. The core concepts for the suite of GENI infrastructure are as follows.

- **Programmability** – researchers may download software into GENI-compatible nodes to control how those nodes behave;
- **Virtualization and Other Forms of Resource Sharing** – whenever feasible, nodes implement virtual machines, which allow multiple researchers to simultaneously share the infrastructure; and each experiment runs within its own, isolated slice created end-to-end across the experiment's GENI resources;
- **Federation** – different parts of the GENI suite are owned and/or operated by different organizations, and the NSF portion of the GENI suite forms only a part of the overall 'ecosystem'; and
- **Slice-based Experimentation** – GENI experiments will be an interconnected set of reserved resources on platforms in diverse locations. Researchers will remotely discover, reserve, configure, program, debug, operate, manage, and teardown distributed systems established across parts of the GENI suite.

As envisioned in these community plans, the GENI suite will support a wide range of experimental protocols, and data dissemination techniques running over facilities such as fiber optics with next-generation optical switches, novel high-speed routers, city-wide experimental urban radio networks, high-end computational clusters, and sensor grids. The GENI suite is envisioned to be shared among a large number of individual,

simultaneous experiments with extensive instrumentation that makes it easy to collect, analyze, and share real measurements.

The GENI Project Office (GPO) has been charged with identifying the infrastructure suite that could best support NetSE experiments, and the key technical risks for such infrastructure. At present the most critical risks are: (a) the control framework for such an infrastructure suite, which does not currently exist; and (b) the feasibility of creating end-to-end "slices" across a range of underlying technologies.

In response to these risks, the GPO has kicked off a series of community-based planning and prototyping activities. A series of prototypes created by spiral development will "co-evolve" trial experimental infrastructures with the evolving research agenda, and will serve to drive down technical risk and increase community insight into the research utility of various types of facilities. The first stage -- GENI Spiral 1 -- is now being organized, and is expected to benefit greatly from donations and leveraging of existing resources. It will attempt to demonstrate end-to-end slices across a range of technologies, governed by early versions of control frameworks.

There is no pre-ordained outcome for these activities: the resultant GENI infrastructure suite could be the existing Internet, existing testbeds, federations of testbeds, something brand new (from small to large), federation of all of the above, and perhaps a federation with related international efforts.