Workshop Report:

ACM SIGCOMM Workshop on Computer Networking: Curriculum Designs and Educational Challenges

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Abstract

This year's annual ACM Sigcomm Conference featured a one-day workshop entitled "Computer Networking: Curriculum Designs and Educational Challenges." The goal of the workshop was to bring together faculty from a broad spectrum of four-year colleges and universities, industry engineers and scientists, and others with an interest in networking education to discuss curriculum design and teaching practices in the field of computer networks. Eighty-nine people participated in this first-ever workshop focused solely on the educational aspects of the networking field. Workshop activities included panels on undergraduate curricula, laboratory-based courses, and graduate curricula. This report summarizes the workshop's presentations, discussions, and findings, as well as plans for future education-related activities.

1. Introduction

Perhaps reflecting the diverse, dynamic, and rapidly expanding set of topics within the field of computer networks itself, curricula and teaching practices in our field are also continuously in flux – with new topics, new courses, and new approaches to teaching being explored at colleges and universities around the world. Among the approaches towards networking curricula, one finds the more quantitative (electrical engineering) style of teaching networking versus a more software/algorithmic (computer science) approach, the more "hands-on" lab-based approach versus more traditional in-class lecture-based approach; the bottom-up approach towards the subject matter versus a top-down approach. New topics, such as peer-to-peer and mobile networking, and increased interest in more established topics, such as security, are further fueling changes to the content of networking courses. And yet, amidst this constant change and growth, the field of networking is arguably entering "middle age" at forty years old, with perhaps a body of "core" topics emerging that many networking educators feel should be mastered by all. The emergence of core networking material is also evidenced by the inclusion of a number of networking topics in the recent IEEE/ACM 2001 Computing Curricula report [IEEE/ACM 2001].

It is against this backdrop of continuing change and evolution, as well as the emergence of fundamental, core topics in our field, that the 2002 Sigcomm Education Workshop was held.

The workshop itself consisted of three panels - on undergraduate curriculum, laboratory courses, and graduate curriculum. Each panel also had a corresponding breakout session. The topics posed for discussion at the workshop were the following:

- **The development of curricula for a first (undergraduate) course in networking.** What are the "core" topics that should be covered in a first course? Are there are small set of approaches towards teaching such a course (e.g., a more quantitative EE-style versus a more software/algorithmic CS-style; "hands-on" versus in-class lectures; bottom-up versus top-down approaches)? What are the roles of labs and/or programming projects? Which undergraduate multi-course sequences are possible? What is the relationship of such course(s) to the recent ACM/IEEE 2001 Computing Curricula report? What materials can be shared by instructors?
- **Laboratory courses.** What approaches can be taken in developing "hands-on" laboratory-based courses at the undergraduate/graduate level? How do laboratory-based exercises relate to traditional lecture-based courses? What topics might be covered, and how should they best be covered? What software, lab materials, and experiences can be shared?
- **The evolution of graduate-level curricula.** A first graduate-level networking course has often been an accelerated/augmented version of an introductory-level undergraduate course, while more advanced graduate courses have often focused on a single sub-area. Several schools have recently introduced multi-course graduate-level course sequences, some within the context of networking/telecommunications MS and PhD programs. What should graduate courses in our field look like? Which courses in specific subareas are desirable, and what might their content be? Is there a set of advanced, foundational material that applies broadly across the field at the graduate level?

Sections 2, 3 and 4 of this report summarize the presentations and discussions in each of these three areas. Section 6 concludes this report with a listing of resources identified by (or prepared by) workshop participants, as well as a discussion of planned future activities. A copy of this report, a collection of 25 white papers prepared by workshop participants in advance of the workshop, a copy of presentation overheads, and additional educated-related information can be obtained from the ACM SICCOMM Education web pages at http://www.acm.org/sigcomm/education.

2. Undergraduate Curriculum

In brief opening remarks, Shawn Ostermann of Ohio University presented the goals for the first session: *(i)* begin a new discipline-wide discussion of undergraduate networking education; *(ii)* begin the formation of a task force to create a report describing existing programs and outlining different teaching models that work well; and *(iii)* make specific recommendations when “rough consensus” is possible.

2.1 Undergraduate Curricula: Presentations

The presentations contained a wealth of valuable information about networking in general, teaching experiences, example classes and curricula, things to try, things to avoid, and things to ponder. The value of these presentations was not just in their detail, but perhaps more importantly in the tone and direction that they helped set for the discussions that followed. The following summary addresses only the salient points of the presentations that led to the recommendations noted at the end of this section. Readers are strongly encouraged to review the presentations in detail at http://www.acm.org/sigcomm/education.

Russell Clark from the Georgia Institute of Technology led off the morning with the first presentation. He presented a brief overview of Georgia Tech's five undergraduate networking courses and then discussed the first, "Introduction to Networking," in depth. This course is primarily a survey course and does not include a lab component. The course is offered twice a year to groups of up to 120 students at a time. The emphasis is on core concepts and best practices, reinforced with written assignments and socket programming. The presenter set the stage for later discussions with a final slide on "Challenges and Opportunities" that included:

- Top-down vs. bottom-up vs. neither– how should we teach networking?
- Theory vs. hands-on?
- How much programming and when?
- Dealing with large class sizes

Ralph Droms from Cisco Systems followed next, with the perspective of an academic researcher who recently moved from Bucknell University to Cisco Systems. The presentation focused on the experiences gained in teaching a networking course for many years and the lessons learned. Different from the program at Georgia Tech, Bucknell offers an introductory course with hands-on exercises, and involves a smaller number of students. The course includes a weekly lab component that covers topics ranging from packet tracing to implementing application protocols. The course culminates with a final project involving a large, distributed simulation. The presentation concluded with a pair of open questions that many have faced and pondered over the years: *(i)* how do we get students to use existing tools rather than "reinventing the wheel"; and *(ii)* how do we foster "problem analysis" and lead students away from their tendency toward "design by emacs"?

The third presentation, by Michael Greenwald of the University of Pennsylvania, emphasized his University's challenges in integrating a large and diverse student population that includes computer scientists, electrical engineers, and telecommunications engineers. The scope of the problem was emphasized by a listing of the university's 15 courses in networking-related areas. Of particular interest was the discussion of identifying "who are our students?" when the population includes CS, EE, Business, and Liberal Arts majors. Each of the student groups has good reasons for needing to understand computer networking, but seemingly tackles the problem from a different angle. His presentation led to discussions on efficient use of classroom and instructor time in the face of these competing demands.

The next presentation was by Dave Morgan of Fidelity Investments, who provided insight into the kinds of jobs and experiences that undergraduate students find after leaving the university. He is involved in hiring 5 to 10 new college graduates each year for a unit with roughly 500 IT professionals. Among the skills valued in new undergraduate hires is an ability to use common tools, and experience in working with teams. Experience at Fidelity Investments has shown that a common problem among new hires is their failure to understand and anticipate the amount of network traffic caused by the new network applications that they design. Lack of first hand measurement and monitoring experience in school is seen as contributing to the problem and led to discussions of possible laboratory exercises in class.

The final presentation was by Craig Partridge from BBN and the Chair of ACM SIGCOMM. Craig Partridge emphasized the importance of having students "write code". He stressed that requiring students to write software is the best way to get them to internalize and understand advanced concepts. It has the further benefit of helping them recognize when they do not fully understand the intricacies of a networking topic. Finally, it leaves them with a marketable skill, which he stated should always be a goal in an undergraduate course. In addition to the benefits of having students write code, he added that it carries the usual burdens of forcing the instructor to make judgments about how much one can push the students without losing large portions of the class.

2.2 Undergraduate Curricula: Breakout Session

The afternoon break-out session on undergraduate curricula continued the lively discussion begun during earlier presentations, undertaking the challenge of identifying the most important concepts that needed to be part of an undergraduate networking curriculum. There seemed to be a general consensus throughout the day that much of what a practicing expert in networking needed to understand would need to come from a graduate degree, and that programs with the expertise and critical mass to provide such a high-quality graduate degree would continue to exist only at a relatively small subset of the world's colleges and universities. At the same time, a widely held belief was that the general concepts of computer networking are sufficiently important that they need to be presented at the undergraduate level to as wide an audience as possible. Supporting this belief is the fact that many colleges and universities now offer (or at least desire to offer) at least one undergraduate course in computer networking.

These discussions led to the consideration of the following question: "If students were only to take a single undergraduate networking course, what topics should that course contain?" It was noted that the hypothetical course being considered would have three basic purposes:

- To teach students enough about computer networks and the implications of their widespread deployment that students can make intelligent choices about how they use such networks;
- To pique the interest of at least a few students in further studying in the area of computer networks;
- To lay a common foundation so that graduate programs can make reasonable assumptions about what students already know.

An alternative phrasing of the question helped sharpen the discussion to focus on what truly constitutes core material – "Inadequate coverage of which topics, if not mastered by students who are supposed to be networking-literate, would be deeply embarrassing to us?" Two additional questions were posed and also helped frame the ensuing discussion: "*(i)* What do students need to understand about the network to use it safely and effectively in their day-to-day activities? *(ii)* What basic knowledge should students have upon entering a graduate program in networking?" It was noted that the answers to these questions are likely not to be the same, but that a topic appearing in the answer to all of these questions would be an excellent candidate for being considered a "core" topic.

With the question of "What would be deeply embarrassing if students did not know?" as a "prod" for identifying core topics, the breakout discussion group began the process of identifying such topics. There seemed to be rough consensus that the topics shown below in Table 1 should all be covered in an undergraduate networking course. We group the topics here by general area for clarity. The reader should not infer from this ordering that we are recommending a "bottom-up" over a "top-down" approach as both approaches have merit, as do their variations.

Physical network basics

- Digital channels
- Errors and error detection
- Understanding of one shared media access protocol (e.g., CSMA)
- A little bit about wireless LANs
- Shannon and Nyquist limits

Concepts

- Circuit switching vs. packet switching
- Framing and encapsulation

Network interconnection

- Moving packets through multiple networks (routing, internetworking)
- Addressing and forwarding

Protocols

- What a protocol is and how it is specified
- Reliable windowed/pipelined data transfer in the face of errors (including basics of TCP)
- Congestion control

Exposure to

- Client/Server programming
- Socket programming
- Managing and configuring a remote device
- Current application protocols and how they work

Recurring themes

- Security as a daily reality
- Encryption as a solution
- Elements of performance (transmission, propagation delay)

Table 1: A First Pass at Important Undergraduate Networking Topics

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Workshop participants noted that the material on security was particularly important and should be a recurring theme throughout the course. The emphasis should be on "what all students need to understand about network security", not just (or even) the theory underpinnings of security. In particular, the following topics should be addressed at appropriate points in the class: using checksums to protect data, implications of clear-text passwords, the implications of using credit cards on the web, authentication, privacy (e.g., using PGP in e-mail).

2.3 Where do we go from here?

The topics listed in Table 1 are the result of an admittedly short and time-constrained discussion at the workshop. Nonetheless, we were sufficiently encouraged with the amount of "rough consensus" that we agreed to take the next logical step. Our next goal is, therefore, to begin the evolutionary process of converting the minimal list from Table 1 into a SIGCOMM-sponsored supplement to the IEEE/ACM 2002 Computing Curriculum recommendations. Interested parties are encouraged to contact Shawn Ostermann at ostermann@cs.ohiou.edu to become involved in this process.

3. Lab-based courses

Traditionally, computer networks courses have not provided students with hands-on access to networking equipment and software. In fact, courses that expose students to actual network environments are still mostly absent in an undergraduate curriculum. While introductory networking courses have a tendency to teach networking concepts at a relatively abstract level, lab courses emphasize how networking concepts are applied in an operational network. The basic assumption for offering a lab-based course is that hands-on lab exercises lead to a deeper understanding of networking principles. Most lab courses are offered as a second course in computer networks. Alternatively, an introductory network course can be supplemented with lab exercises.

The lab panel at the workshop surveyed different approaches that can be taken in developing "hands-on" laboratory-based courses at the undergraduate and graduate level. The lab panel consisted of designers and/or instructors of lab-based courses, and included Ann Burroughs (Humboldt State University), Magda El Zarki (University of California at Irvine), Doug Comer (Purdue University), Michael Williams (University of Akron), and Nick McKeown (Stanford University). The panel was chaired by Jörg Liebeherr (University of Virginia).

Ann Burroughs shared her experience with setting up a network teaching lab at Humboldt State University. The Computing Science Department at Humboldt State offers two undergraduate courses: a breadth-oriented course (Telecommunications) which is a core requirement, and a depth-oriented elected course (Network Design and Implementation). Ann Burroughs' networking lab is integrated into the Telecommunications course. The lab equipment at Humboldt State was established with an equipment donation of Cisco 7000 routers obtained through the NSF-supported Internet Teaching Lab project [CAIDA], which distributed sets of Cisco 7000 routers to over 25 educational institutions for the purpose of setting up teaching labs. Ann Burroughs discussed issues involved in integrating a lab component into an existing lecture course.

Doug Comer's Xinu lab was one of the first teaching labs for computer networks education. Established in 1984, the Xinu laboratory is used for research and instruction in operating systems and networks, and includes 20 workstations, 24 front-end workstations on Gigabit Ethernet, several back-end systems, and more than 20 network processors, as well as IP routers and switching equipment. Doug Comer gave examples of lab experiments for undergraduate and graduate students in the Xinu Lab. At the undergraduate level, lab exercises include network programming, where students build a client and server application and a concurrent web server, measurement experiments, where students compare the throughput of Ethernet hubs and switches, and protocol analysis experiments, where students study IP fragmentation and trace TCP connections. As examples of graduate-level lab exercises, students design and implement a software-based IP router with certain advanced features, such as multicast, NAT, or SNMP. Other lab exercises ask students to design and implement an IPsec box on a network processor platform, and a voice service over IP.

Doug Comer discussed how a lab course fits into a networking curriculum. An undergraduate course in computer networks provides breadth and exposes students to the concepts and the terminology of networking. The outcome of such a course is that students can state the purpose and function of hardware and software components of a network and know the role of communication protocols. In addition, students learn to write programs using a computer network. A graduate curriculum in networking strives for complete mastery of the subject, that is, understanding the design and implementation of protocols, being able to build correct and efficient system components, knowing how to architect large-scale networks, and being able to discuss tradeoffs and limitations of computer networks.

Doug Comer emphasized that lab courses are absolutely essential for a networking curriculum. Labs permit students to "learn by doing." Labs also reinforce concepts that are presented in a lecture and provide a concrete understanding of details. Doug Comer pointed out that the equipment in a lab does not need to use the most recent or fastest technology, and that a lab course with old equipment should always be preferred to not offering a lab course.

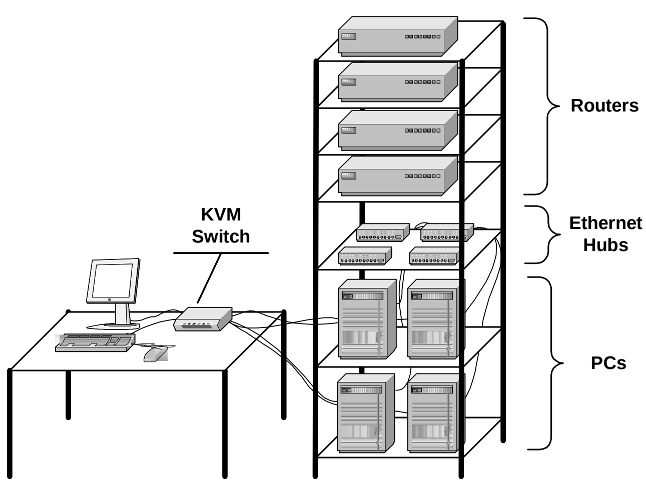

Figure 1. Open lab approach.

Magda El Zarki discussed the design of a lab course with an *open lab* approach, where *open lab* refers to the fact that the lab equipment is located in a public area and that students perform lab experiments without supervision. The equipment for the open lab networking course is shown in Figure 1. It consists of four Linux PCs, four routers, and four Ethernet hubs. The PCs and routers are controlled from a single keyboard and monitor which is attached to a Keyboard-Video-Monitor (KVM) switch. The lab equipment is not connected to the Internet. An advantage of a rack-based lab is that the lab equipment can be easily duplicated. Currently, UC Irvine has five of the racks shown in Figure 1, and additional racks are being added.

Using the open lab approach, an instructor can manage a lab course with 50 - 70 students with only one teaching assistant and one grader. The lab course is taught every quarter to senior graduate students and first year graduate students. In the lab course, students complete eight labs over a period of 10 weeks. The lab topics include single segment networks, static routing, routing protocols, LAN switching, TCP and UDP, multicast, NAT, DHCP, DNS, and SNMP. The lecture component of the lab course consists of one three-hour long lecture per week. Each lecture gives an overview of the topics of a specific lab and demonstrates some of the experiments on equipment that is located in the lecture room. Each lab is structured in three phases. In the first phase, the “prelab”, students read material and answer prelab questions which prepare them for the lab exercises. In the second phase, the “lab exercises”, students work on the lab equipment, following step-by-step instructions given in a lab manual. Lab experiments consist of traffic measurements with a protocol analyzer tool. In the third phase, the “postlab report“, students analyze the data that was gathered in the lab and prepare a report.

Michael Williams gave a presentation on the participation of the University of Akron in the Cisco Networking Academy program. The Cisco academy is a partnership program of Cisco Systems with educational, business, government, and other organizations, that evolved from a program to support a network curriculum at high schools. Cisco academy courses are offered as a combination of hands-on lab exercises and online study programs. Colleges and universities participate in the program by providing space, purchasing equipment for lab exercises, and providing personnel for teaching and supervision. The teaching material is supplied by Cisco Systems. The Cisco academy generally offers two certification programs, the Cisco Certified Network Associate (CCNA) and the Cisco Certified Network Professional (CCNP). At the University of Akron, the CCNA and CCNP program each consist of four eight-week courses, which are designed to be completed in two semesters each. Students enroll in the courses as for any other credit course. The courses can be applied to some bachelor’s and associate degree programs at the University of Akron.

In his presentation, Nick McKeown gave an overview of his network infrastructure labs. The goal of the labs is to have students design, implement, deploy and debug their own infrastructure elements, such as IP routers, Ethernet switches, and elements of their own creation. The networking labs developed by Nick McKeown have a hardware component and a software component. NetFPGA [NetFPGA] is a hardware platform, which consists of a circuit board with eight Ethernet interfaces and user-programmable FPGAs. Students use these boards to architect, design and deploy their own hardware in an operational network. For example, students implement an Ethernet switch, an IP router, or a firewall. The design process follows the industry standard flow. That is, students start with an implementation on a Verilog platform, followed by a simulation and verification phase, and a synthesis phase. At the end of the design process, the software is downloaded to the circuit boards and tested on a network that is connected to the campus network. A prototype of the NetFPGA platform has been developed in 2002, and classroom use is planned for 2003.

The software component of Nick McKeown's lab is called *virtual router* [Virtual Router]. The virtual router labs are intended for large networking classes with more than one hundred students, where it is not practical to provide each student with a dedicated computer with kernel-level access. In the virtual router lab exercises, students architect, design and deploy an IP router as a user-level system. Virtual router clients can be interconnected to form a virtual network topology for routing IP packets. The virtual router implementations have been used since 2001, and a release of the platform to other institutions is planned for summer 2003.

In the breakout session, which was led by Shiv Kalyanaraman (Rensselaer Polytechnic Institute), workshop participants identified different styles of labs that are being offered at various institutions. One broad group of lab exercises focuses on network programming. Some programming exercises focus on socket programming exercises, where students build application-layer services. Other programming exercises ask students to build network components, generally involving kernel-level programming or special hardware, such as FPGAs or network processors. Another group of lab exercises focuses on configuration and measurements of networking equipment. These labs try to find a balance between teaching an understanding of networking hardware and software and vendor-specific configuration skills.

There are numerous network simulation tools available that can be used in a lab course (ns-2 [ns], Opnet [Opnet], SSFnet [SSFnet] and GloMoSim [GloMoSim]). Simulation packages seem to have advantages when teaching very large classes. Recently, several emulation environments have become available that offer the opportunity to conduct lab exercises in a mixed hardware and software environment. The X-Bone [X-Bone] software can be used to deploy network-level services by tunneling IP traffic between X-bone capable systems. Some emulation platforms (Entrapid [Huang 1999], Vmware [Vmware]) can execute multiple operating system images, and can emulate a network with multiple routers and hosts on a single workstation. Emulab [Emulab] is a network emulator at the University of Utah that consists of several hundred PCs in racks that can be remotely configured.

The discussions in the panel and the breakout sessions showed a broad spectrum of lab courses that are used in computer networks education. A comparison of the different approaches (programming, configuration, measurement, and simulation/emulation) made clear that each approach has a distinct set of advantages for teaching certain aspects of computer networks.

The fact that most of the lab courses discussed at the workshop were introduced only recently points to a trend of faculty beginning to introduce labs into the networking curriculum. Instructors commented on the significant student interest in lab courses, and the generally overwhelmingly positive feedback. A problem with creating a new lab course is the considerable initial time commitment by instructors. Thus, the community could greatly benefit from a repository of existing computer networks lab courses that allow instructors to take advantage of earlier efforts at other institutions.

4. Graduate Curriculum

Just as schools are experiencing changes within their undergraduate networking curricula, so too are they experiencing change at the graduate level. These changes are being fueled by increased student interest in networking at both the undergraduate and graduate level, as well as by developments within the field itself. With more undergraduate students taking an introductory networking course, workshop participants noted that more students are arriving to graduate school ready to take advanced networking courses. Workshop participants also noted a marked increase in the number of graduate students interested in network-related courses. The increase in student preparedness, the increase in interest, and the ever-increasing growth in the scope of the field itself has resulted in tremendous demand for a larger and richer selection of graduate-level courses. Several schools have responded to this demand by creating MS and PhD level programs with specializations in networking and/or telecommunications.

The goal of the session on the graduate curricula was to survey various schools' approaches towards defining a graduate networking curricula. A number of questions were posed to the panel (and later discussed during the breakout session): *(i)* to what extent are the first graduate courses being taught an accelerated first (introductory) course in networking versus an advanced course that would build on a prerequisite introductory course? *(ii)* is there an emerging set of *graduate-level* "core" material, that might build on undergraduate core material, such as that listed in Table 1? *(iii)* to what extent do graduate level courses focus on theory versus practice, *(iv)* what are expectations of industry regarding graduate-level courses, and *(v)* what is being done at your school?

The graduate curriculum panel participants were Ken Calvert (U. Kentucky), Scott Jordan (UC Irvine), Raj Yavatkar (Intel), and Ty Znati (U. Pittsburgh, and Program Director in the NSF CISE Division of Advanced Network Infrastructure and Research). The panel was chaired by Jim Kurose (University of Massachusetts).

Ken Calvert began the graduate curricula panel by describing the first networking course at the graduate level at the University of Kentucky. The course is an advanced introductory course that does not assume a previous course in networking. Topics covered include many of those listed in Table 1: channels, bandwidth and coding; framing, errors and ARQ; routing; transport protocols; queueing models; congestion control and avoidance; QoS; MAC protocols; application protocols (HTTP and SMTP); digital media, and the future Internet. The course emphasizes principles – important topics that have a more-than-5-year half-life, and illustrates these principles with real-world examples. There is a significant programming component to the course.

One important aspect of an introductory graduate-level course noted by Calvert (and seconded by many others at the workshop) was the varying degree of background and preparedness among incoming students. While some students have had no previous exposure to networking, other students may have already had an introduction to networking at the undergraduate level. Backgrounds even varied among those who have had previous exposure to networking – some students have had a more theoretically-oriented first course, while others have had more of a standards-based course, while yet others have had primarily a programming-oriented course. Calvert suggested that defining a topical interface between an undergraduate course, and a subsequent first graduate-level course would be a good first step in solving this problem.

Scott Jordan of the University of California at Irvine (UCI) was the next panelist. He described the proposed Masters and PhD program in "Networked Systems" at UCI. The new program is a collaborative effort between the Department of Electrical and Computer Engineering, and the

Department of Information and Computer Science. The program defines three core courses (Computer Networks, Computer Network Laboratory, Network Systems Seminar); five concentration areas (networks, performance, middleware, communications, and operations research), each with a number of courses; and two breadth areas (computer systems engineering, and management of technology).

Ty Znati from the University of Pittsburgh, also currently a Program Director in the Advanced Networking Infrastructure and Research Division at the National Science Foundation, then described the Telecommunications Ph.D. program at the University of Pittsburgh. The degree is awarded as a Ph.D. in Information Science with a Telecommunications concentration. Like the proposed PhD program at UCI, the Pitt program clusters graduate courses into different areas: networking, communication systems, computer communications, telecommunications administration, telecommunications economics and policy, human communications, and wireless communications. The program offers a 24-credit certificate program, a 36-credit masters degree, and the PhD degree.

Raj Yavatkar from Intel provided an industry perspective on graduate education. He began by noting two particular deficiencies that he often finds in incoming students: that they have little hands-on experience, and not enough of an understanding of *system* design and architecture. He then identified the background that he would like to see in all graduate-level students: the basics of efficient protocol design, security as a first class object, performance analysis and evaluation, and system design and architecture. Raj Yavatkar then outlined the contents of two graduate-level courses that would prepare students well for industry positions. He noted that these two courses built on an assumed undergraduate course in networking, and emphasized that one hands-on project and one simulation-oriented project were a critically important component of such courses. The Intel IXA network processor program was noted as an example of how projects have (and could be) integrated into graduate level courses.

While the undergraduate breakout session was able to find a rough consensus on core topics that might be taught in a first undergraduate networking course, no such consensus was reached in the graduate curriculum discussion. The one common theme that did emerge was the recognized need to teach students advanced foundational material that “has a long shelf life” (i.e., would be useful to students for many years to come), and much of the discussion centered on what specific topics should be taught in such a course. Performance evaluation (modeling, simulation, and experimental design), a “science” of protocol design, and large-scale system building were topics that many felt should be taught in such a graduate “core” course.

5. Conclusions

While a one-day workshop can only begin to address the many issues facing networking educators, the general consensus was that the workshop had been an extremely valuable forum for learning about what others are doing, exchanging ideas, and promoting thought-provoking discussion. A number of resources and ongoing activities have resulted from the workshop, and can be accessed via the ACM SIGCOMM Education web page (http://www.acm.org/sigcomm/education):

- A listing of networking courses is being maintained by Maurice Aburdene at http://www.eg.bucknell.edu/~aburdene/networkcourses/. In addition, a list of courses; has been maintained by the Internet Engineering Curriculum group at CAIDA: http://www.caida.org/outreach/iec/courses/;
- A listing of lab-related courses and resources is being maintained by Sanjay Jha at http://www.cse.unsw.edu.au/~sjha/netlab.html;
- A mailing list for people interested in discussing issues related to networking education: sigcomm_education@cs.umass.edu;
- A compendium of white papers submitted in advance of this workshop to stimulate thought and discussion ;
- Organizational planning for a follow-up workshop.

More information about these activities can be found at http://www.acm.org/sigcomm/education. All members of the networking community are invited to become involved in these efforts.

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References

[CAIDA] ITL – Internet Teaching Laboratories, http://www.caida.org/outreach/itl
[emulab] netlab – Based on emulab, http://www.emulab.net
[GloMoSim] GloMoSim – Global Mobile Information Systems Simulation Library, http://pcl.cs.ucla.edu/projects/glomosim/
[Huang 1999] X.W. Huang, R. Sharma, and S. Keshav, The ENTRAPID Protocol Development Environment, Proc. IEEE Infocom '99, March 1999. http://www.cs.cornell.edu/skeshav/papers/entrapid.pdf
[IEEE/ACM 2001] CC-2001 Task Force, Computing Curriculum (Final Draft), http://www.computer.org/education/cc2001/final
[NetFPGA] The NetFPGA Project, http://klamath.stanford.edu/NetFPGA/
[ns] The Network Simulator – ns2, http://www.isi.edu/nsnam/ns/
[OPNET] OPNET homepage, http://www.opnet.com
[SSFnet] The Scalable Simulation Framework, http://www.ssfnet.org
[Virtual Router] The Virtual Router Project, http://klamath.stanford.edu/vr/vr.html
[vmware] The vmware Homepage, http://www.vmware.com/
[X-Bone] The X-Bone –a System for Automated Overlay Network Deployment, http://www.isi.edu/xbone