CARNEGIE MELLON'S DEPARTMENT OF ENGINEERING AND PUBLIC POLICY

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ABSTRACT

The Department of Engineering and Public Policy (EPP) is an unusual department in the College of Engineering at Carnegie Mellon University. It focuses on problems in technology and public policy in which the technical issues are of central importance. EPP began as an undergraduate program in 1970 and became an academic department in 1976. At the graduate level, the department offers a research-oriented Ph.D. for students with backgrounds in science and engineering. This paper briefly summarizes the history of the department, discusses the institutional arrangements, which allow it to function, describes the academic programs, and briefly summarizes current research.

Keywords: Engineering, Education, Engineering Systems, Technology Management, Technology Policy

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1. INTRODUCTION

The engineering college at Carnegie Mellon University houses five traditional departments (chemical, civil and environmental, electrical and computer, mechanical, and materials science and engineering). In addition, for approximately 30 years, it has also been home to a very non-traditional Department of Engineering and Public Policy (EPP). EPP was originally established as an undergraduate educational program, designed to add additional dimensions and skills to the education of engineering students who planned conventional engineering careers. Beginning in the late 1970s a research-oriented doctoral program was added. This paper provides a brief overview of the department's history and its current programs in education and research.

2. THE INSTITUTIONAL SETTING

In order to understand EPP, one must first understand Carnegie Mellon's unusual institutional setting. The university was founded at the turn of the century by Andrew Carnegie as the Carnegie Institute of Technology. In establishing the school, Carnegie was not setting out to create a major research institution, but rather a high-quality vocational school for the sons and daughters of Pittsburgh mill-workers. By the period between the two world wars, the school had grown into a good regional engineering school, with a reputation of educating students in the practical solution of problems drawn from the real world. Since such problems typically did not fit neatly into traditional disciplines, engineering at "Carnegie Tech" took on a distinctly interdisciplinary character.

Carnegie Mellon's emergence as a major US research University occurred in the period following the Second World War (the name change occurred in 1967, when Carnegie Tech was merged with the Mellon Institute, an industrial research laboratory). During the post-war period, the University undertook two very important institutional innovations. First it built a new business school (the Graduate School of Industrial Administration or GSIA) by assembling an interdisciplinary team of quantitatively-oriented faculty. Following the institutional tradition of doing empirical work on real world problems, faculty in this group, which included Herb Simon, James March, and Dick Cyert, revolutionized modern social science, developing the Carnegie Behavioral School of social science (Bower, 1968). In addition, GSIA pioneered

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modern quantitative approaches to business education that are now widely used in business schools around the world.

The development of computer science was the second key institutional innovation during the post-war period. At most universities, computer science grew out of mathematics and electrical engineering. At Carnegie Mellon, it also grew out of GSIA and psychology. That broad interdisciplinary background, combined with many years of strong funding by the Advanced Research Projects Agency of the Department of Defense (National Research Council, 1999) led to the creation of one of the strongest computer science units anywhere in the world.

By the time Richard Cyert became President of Carnegie Mellon in 1972 the institution had clearly decided that it wanted to be a leading research university. But how does a small private university, with modest resources "play with the big boys"? Clearly good ideas are a necessity, but they are not sufficient. Once others with larger resources understand those good ideas, they may easily surge ahead. Cyert recognized that the University needed to look for areas in which it could not only get, but could also keep, a competitive advantage. With strong interdisciplinary research traditions already established in engineering, GSIA and computer science, addressing problems at the boundaries between traditional disciplines, something that most universities find it very hard to do in a stable way, emerged as an obvious area for comparative advantage.

It was in this environment that in the late 60's and early 70's a group of faculty in the Engineering College decided that, while undergraduate engineering education was doing a fine job of providing technical skills, in the modern world engineers should also have an understanding of the relation of their technology to the broader society. Thanks to the efforts of Rod Williams, Herb Toor, Bob Dunlap and others, this concern led to the creation of a set of undergraduate double major degree programs with all five of the traditional engineering departments, the first academic program in what would shortly become the Department of Engineering and Public Policy.

3. FACULTY ARRANGEMENTS

In most universities, interdisciplinary joint appointments between academic departments are a recipe for disaster, especially for untenured faculty. However, because of Carnegie Mellon's unique institutional environment, it has been possible to build EPP largely with true 50:50 joint appointments between all five of the traditional engineering departments, and with four different social science units in three other colleges.

There are currently 26 tenure track faculty in EPP. Thirteen tenure-track faculty are funded by EPP. Twelve hold joint appointments with one of the other five traditional engineering departments or with one of four social science units in three other colleges (Humanities and Social Sciences, Heinz School of Business, Graduate School of Industrial Administration). Thirteen, called "affiliated faculty," do not receive salary from EPP, but in all other respects are equivalent to jointly appointed faculty (e.g., senior affiliated faculty vote on tenure, etc.). As of 1998, a total of 20 (54%) of the tenure-track faculty in EPP are tenured. There were also 11 research track and special faculty and 16 adjunct and part-time faculty in EPP.

As of 1996 average annual publication rates for faculty supported on the academic budget of the department were: 9 refereed papers/year, 7 book chapters, opinion pieces, etc./year, and 0.4 books authored or edited/year. Publication rates for affiliated faculty were: 8 refereed papers/year, 5 book chapters, opinion pieces, etc./year, and 0.6 books authored or edited/year.

4. THE UNDERGRADUATE PROGRAM

The department offers double-major Bachelor degree programs with each of the five traditional engineering departments in the college (e.g., Bachelor in chemical engineering/engineering and public policy) and with the School of Computer Science. These joint degree programs, which have been offered since 1971, are now chosen by about 10 percent of all undergraduate engineering students at Carnegie Mellon. These double major programs all lead to fully accredited engineering degrees that prepare students for traditional engineering careers. EPP double-major engineers are not educated to be a different kind of engineer. Rather, their education is intended to enable them to be better, more socially responsible engineers in the traditional engineering fields. In addition to these double major degrees, the department also offers a minor in "Technology and Public Policy" for students outside of engineering and computer science.

All the undergraduate degree programs in Engineering and Public Policy combine a strong foundation in mathematics and physical sciences, and the development of engineering skills in a specific engineering field, with a rigorous preparation in the analysis of social and political problems. The curricula include subject matter which is not part of traditional engineering or social science curricula, but which contains elements of each. This is accomplished through Engineering and Public Policy technical elective courses, social analysis elective courses, and through participation by each student in two interdisciplinary problem-solving projects. Problem areas for these projects are drawn from local, state, and national situations and include such topics as industrial automation and robotics, environmental control, telecommunication and computer technologies, product safety, and energy systems.

To make the double major work, EPP takes over all of the technical and non-technical elective courses in the traditional engineering major and shapes them to meet the needs of the second degree. Table 1 provides a general illustration of how this works. The double major degree is completed in the same four years as the traditional single major, but in some cases requires a few more units, and typically involves a more demanding set of courses. As indicated in Table 1, four of the technical electives in a traditional major get replaced by EPP technical electives. The Humanities, Social Science and Fine Arts electives are replaced by Social Analysis electives. Two EPP project courses and two Probability and Statistics courses are worked into restricted elective slots. The details of how the double major curricula work out are different for each traditional department. Both as an aid to students, and to clearly demonstrate compliance with ABET accreditation requirements, the undergraduate catalog spells out the course requirements for each of the five double major programs and provides equivalency tables which show exactly how the single and double major curricula compare with each other.

"Project courses" are an important part of the department's undergraduate programs. The typical project course involves about 25 students, half of whom are junior or senior engineering students in EPP and half of whom are a mixture of first year master's students in The Heinz School of Public Policy and Management and undergraduate policy majors in Social and Decision Sciences. Projects address some real world problem in technology and public policy, usually with an outside client for whom the work is being done. Students start the semester with a vaguely defined problem area and various background materials that they must use to define and shape a workable problem and then undertake the necessary analysis to get the problem solved. There are usually two faculty advisors, one from engineering and one from social sciences together with one or two student managers. Over the first couple of weeks of a project, the students work on developing a thorough understanding of the subject and defining the focus of the work they will do. About a third of the way into the semester, students make a first formal presentation at which they present their proposed research to an outside review panel of experts who represent different expertise and points of view in the problem field. The review panel assists the students by providing critical comments on the way in which they have structured the problem and by suggesting various resources and information sources. About two-thirds of the way through the semester, students make a second presentation to the project review committee at which they present a progress report and receive steering suggestions from the review panel. At the end of the semester, the students prepare a final written project report and make a final verbal presentation of their findings and conclusions to the review panel. Of course, it's impossible for 25 students to work a single problem all together, so much of the work in project courses gets done in smaller working groups of four to eight students.

Project courses serve several important educational functions. First, they are the one place where students get an opportunity to put together the various technical and social analysis components of their education and gain hands-on experience working on real world problems. Second, project courses provide valuable opportunity for students to develop and refine their verbal skills which turn out, in the real world of daily engineering practice, to be every bit as important for success as the more traditional mathematical and quantitative analytical skills.

Project courses are very demanding, and it is not at all unusual for students to complain about them while they are going through the experience. However, in three extensive surveys we have done over the past 20 years of all EPP undergraduate alumni, the consistent message we have received is that "project courses were the single most valuable educational experience that I had in my four years at Carnegie Mellon."

The majority of the double-major graduates in Engineering and Public Policy pursue conventional engineering careers, using the additional dimension in their background to improve the quality, sensitivity, and social responsiveness of their work, and the work of their colleagues. Many who begin in conventional engineering careers later migrate into positions with responsibilities that make special use of their EPP education. A number of graduates elect careers with local, state, or national government or with policy research and consulting firms. Some choose to continue their formal education, doing graduate work in an engineering discipline, in the social sciences, law, or in an interdisciplinary program.

As of 1998 EPP had graduated 550 double major Bachelor of Science students and had a double major enrollment of 80. Approximately 80% of double majors go into traditional engineering careers. Eight students are currently enrolled in the newly created Minor in Technology and Public Policy for non-engineering students.

5. THE GRADUATE PROGRAM

EPP offers a research-oriented Ph.D. We admit terminal MS students only in special circumstances.

The graduate program in Engineering and Public Policy educates technically skilled men and women at the doctoral level to be leaders in policy-focused research. We work on policy problems where the technology matters --where technology cannot be treated as a "black box." Policy-focused research differs from policy analysis in three important ways: it takes a longer-term perspective; it takes a more fundamental perspective; and it may focus on the development of theory, and of analytical tools and techniques, as well as on solving specific problems.

Perhaps the quickest way to understand what EPP's graduate program is all about is to look at a few of the titles of the approximately 100 Ph.D.s the department had granted by 1999. Table 2 summarizes the most recent ten.

The Ph.D. in EPP requires a rigorous program of courses and research accomplishment. The courses include a series of core classes on fundamental approaches and methods for engineering and public policy; required classes in statistics and economics; electives in engineering, sciences and mathematics; and electives in the social sciences. Research experience and efforts begin very early in the academic program, leading to a first research paper (hopefully, of journal quality) after the third semester (this is the first part of the qualifying exam process), and continuing through the development of subsequent papers and the Ph.D. thesis.

Table 1: Comparison of the traditional undergraduate engineering curriculum with the EPP double major undergraduate curriculum.

Courses in the traditional major	**Courses in the EPP double major**
Common freshman year	Common freshman year
Required engineering courses	Required engineering courses
Free electives	EPP projects
Technical electives	4 EPP technical electives 2 courses in probability and statistics
Humanities, social science and fine arts electives	6 social analysis electives including microeconomics and decision analysis

Table 2: Last 10 Doctoral Dissertations completed in the Department of Engineering and Public Policy as of 1999.

James C. Corbett	An Assessment of Air Pollution and Environmental Impacts from International Maritime Transportation Including Engineering Controls and Policy Alternatives.
John Chung-I Chuang	Economies of Scale in Information Dissemination over the Internet.
James N. Follin	Environmental Risks, Decision-Making and Public Perception: A case study involving environmental impact statements
Heather L. MacLean	Life Cycle Models of Conventional and Alternative-Fueled Automobiles
Kara Morgan	The Development and Evaluation of a Risk Ranking Method
Donna M. Riley	Human Factors in Exposure Analysis for Consumer Paint Stripper Use
John Shultz	The Risk of Accidents and Spills at Offshore Production Platforms: A statistical analysis of risk factors and the development of predictive models
Neil A. Stiber	Decision-Making Tools for Environmental Cleanup and Redevelopment
Daniel Teitelbaum	Technological Change and Pollution Control: An adaptive agent-based analysis
Rahul Tongia	Issues in Electric Power in India: Challenges and Opportunities

The qualifying exams occur at the end of a student's third semester. They include a "Part A" research paper and a "Part B" take home exam. The Part A paper is developed, written and submitted by the student, followed by an oral presentation and subsequent question and answer session with the faculty. Questions can relate directly to the analysis presented in the paper or to more general disciplinary knowledge and skills. The Part B exam is taken and written over a 5-day period and involves a problem in which students must analyze and evaluate a realistic (and generally current) problem with engineering, science, social science and policy content. All students receive the same problem. The written exam reports are graded blindly by the faculty (this means that the faculty do not know which student wrote which report until the grading is completed).

As of 1999, the department had graduated 100 Ph.D.s and had a graduate enrollment of 40. Doctoral graduates go to policy-oriented research careers in universities (~45%), industry (~25%), government and national laboratories (~15%), consulting firms and think tanks (~15%).

6. RESEARCH IN EPP

There are many public- and private-sector policy problems about technology in which the technical details can be treated as a black box. However, there are some problems in which understanding and dealing with the technical details is absolutely essential if one is going to develop good understanding and appropriate policy solutions. Research in EPP focuses on that sub-set of public and private sector policy problems in which the technical details are important. In choosing this focus, we make no statement about the relative importance of such problems. We simply note that our particular comparative advantage lies in addressing such problems.

Within the large domain of policy problems in which the technical details matter, most research in EPP lies in one of four areas:

- energy and environmental systems;
- risk analysis and communication;
- information and communication technologies; and,
- technology policy, including issues in technological innovation, green design, industrial automation, productivity and engineering education and the technical workforce.

Within the context of these four focal areas, the department also addresses issues in technology and economic development, focusing in particular on India and China. It frequently undertakes the development of new software tools for the support of policy analysis and research. From time-to-time it undertakes work on issues in arms control and defense policy.

The research style in the department has always involved collaboration among groups of faculty and students. Recent years has seen a growth in the scale of these collaborations, and the establishment of several formal research Centers, including: The Center for the Integrated Study of the Human

Dimensions of Global Change; the Green Design Initiative; the Center for Energy and Environmental Studies; the Center for the Study and Improvement of Regulation; the Brownfields Center; a center-like set of activities in internet commerce, telephone, etc.; a similar set of activities in risk analysis, ranking, communication; and a set of activities involving energy and information systems in India. Because space is limited, I will briefly describe just three of these.

Center of the Integrated Study of the Human Dimensions of Global Change

The NSF-supported Center for Integrated Study of the Human Dimensions of Global Change involves a collaboration of over thirty scientists from fourteen institutions in eight countries around the world. Center activities are coordinated from the Department of Engineering and Public Policy at Carnegie Mellon University.

The philosophy and focus of the Center are reflected in its name:

- *Integrated Study* - because real world problems do not respect disciplinary boundaries and demand the combined and coherent application of social and natural science knowledge.
- *Human Dimensions* - because both the deliberate and reactive actions of humans shape the world around us. These actions are motivated by aspirations about individual, social and environmental welfare and informed by subjective perceptions and an evolving understanding of the world.
- *Global Change* - because local human activities often follow a repeated pattern on a global scale. Local decisions can and do have global consequences, often unintended. In many domains, existing national/international organizations are unable to exercise adequate oversight or control.

The Center has four principal objectives:

- to bring together fields of study that reflect our understanding of the patterns of human activity and environmental change in the real world, but which have been treated as disparate disciplines in traditional academic practice;
- to explore the limitations of current knowledge and analytical methodology in application to problems of global environmental change and develop new approaches for their framing and analysis;
- to study how assessments are used by decision-makers and develop new methods for framing and analyzing problems in public policy which involve substantial natural and social scientific issues; and
- to conduct outreach activities including the development of new curriculum material for colleges, communication brochures for the general public, and focused briefings for government and industry decision-makers.

One important product of the Center has been the development of ICAM, the Integrated Climate Assessment Model, a large stochastic simulation model (Dowlatabadi and Morgan 1999; Morgan and Dowlatabadi, 1996) built in the Analytica® software environment (formerly Demos). This environment provides a powerful graphic user interface that represents the model structure in the form of hierarchically organized influence diagrams. Users can explore the model by "double clicking" on various elements, moving down through the model hierarchy until they reach individual model elements, where they can observe the mathematical relationships between variables and read documentation on some of the values being used and the assumptions that have been made. Users can easily substitute alternative values or probability distributions. The model is available at http://www.hdgc.epp.cmu.edu. A demonstration copy of the Analytica® software can be obtained at http://www.lumina.com/software.

In the 1998 version of ICAM, the world is divided into twelve regions. Time is stepped in five-year increments from 1975 to 2100. Demographic and economic processes lead to emissions of greenhouse gases and aerosols. These modify the composition of the atmosphere, and bring about climate change. Climate change leads to various impacts that in turn can affect demographic, socio-economic and ecological processes. It is possible to make policy interventions in energy use, in emissions management, and in adapting to impacts. In some user-selected structural variants of ICAM, economic factors, climate change, and climate impacts can influence the initiation and path of these interventions.

In developing ICAM, we found that uncertainty about the appropriate functional form of different sub-models is sufficiently large, and the difficulty of constructing all plausible alternatives sufficiently great, that it is often best to report results parametrically across a set of combinations of different model structural assumptions, in much the same way that one reports the results of parametric sensitivity studies of coefficient uncertainty. For example, in an application of ICAM-2 designed to explore the probability that a specific carbon tax policy would yield net positive benefits, we found that the probability ranged from 0.15 to 0.95 for the world as a whole, depending upon the structural assumptions made (Morgan and Dowlatabadi, 1996; Casman et al., 1999).

Many climate policy models are designed and solved as long-term optimization problems. In a setting with uncertainties as great as those displayed in ICAM, we doubt the utility of conventional optimization formulations. As an alternative, rather than try to search for the optimal policy, we have set out to search for robust behaviors. Just as in the model environment, real world policy makers will always face great uncertainty. They must observe the world, use what they see together with models to make forecasts, choose what they think is the best strategy at the moment, and then a few years later, repeat the entire cycle. By building simple "decision agents" we have been able to do something very similar within the world of the ICAM model environment. Then, across a range of alternative model worlds we run repeated stochastic simulations of the model and ask, among a range of plausible alternative behavioral strategies which our agents might adopt, which one does best in the face of the uncertainties about both coefficient values and model structures? In the case of the climate problem, a strategy that tracks and attempts to control atmospheric concentration of greenhouse gasses (as opposed to emissions or temperature), using a quadratic penalty function, seems to do best (Dowlatabadi, 1998).

The Green Design Initiative

Carnegie Mellon University began a campus-wide Green Design Initiative in 1992 to promote environmentally conscious engineering, product and process design, manufacturing, and architecture. The initiative involves forming partnerships with industrial corporations, foundations, and government agencies to develop joint research and education programs which improve environmental quality while encouraging sustainable economic development.

Researchers involved in the Green Design Initiative have explored a variety of important problems in green design and life-cycle analysis. For example, they have examined the environmental implications of the use of lead-acid batteries in electric powered automobiles (Lave et al., 1995) and have preformed assessments of a variety of alternative advanced motor fuels (MacLean and Lave, 1998).

One particularly important innovation has been the development of a computer tool that couples a 500x500 input-output table of the US economy with the EPA toxic release inventory, energy use data, and similar information. This tool allows a researcher to estimate the overall environmental impacts from producing a million dollars worth of any of 500 commodities or services in the United States. It provides rough guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the U.S.

The entire supply chain of requirements is included, so that the effects of producing a motor vehicle would include not only the impacts of final assembly, but also the impact from mining of metals, making electronic parts, forming windows, etc. that are needed for parts to build the car. However, the data used are only for production, so impacts of gasoline use and maintenance need to be evaluated separately. Environmental impacts include energy use, air pollutants, hazardous wastes, toxic emissions and dollar estimates of external air pollution costs. Additional information, including an on line version of the I/O-LCA tool can be found under "green design" in the research portion of the EPP web page at http://www.epp.cmu.edu/.

Center for the Study and Improvement of Regulation

As its name implies, the basic motivation of the Center for the Study and Improvement of Regulation is to understand how regulation has (and has not) worked in the past, and then build on the resulting insights, together with results from theory and experiments, to identify and promote a broad menu of new and better approaches to dealing with regulatory issues.

Recent decades have witnessed a remarkable proliferation of regulation designed to safeguard and improve health, safety and the environment. To a very large extent these efforts have succeeded, making the US a safer, healthier and environmentally better country, and pointing the way for similar improvements in many other parts of the world. But, while past hazards were often easy to see, taste or smell, today we must often deal with pollutants or other risks that can not be readily detected with our senses; whose observable effects, if any, may not be seen for decades (and then, perhaps, only in statistical terms). In many cases, the costs of further control or other risk management actions are rising rapidly, while the benefits of some regulatory actions have become highly uncertain. The US and other industrialized societies have begun to run up against limits on our ability to pay, on our freedom of action, and on how we allocate our time and attention. Implemented poorly, future health, environmental and safety regulation could stifle the economy, placing high economic and social burdens on all Americans.

"More of the same" approach will no longer serve the national interest. In today's changed world, we need risk management strategies that have coherent philosophical foundations that incorporate public values and sensibilities, are economically and socially efficient, use the best possible science, and are informed by the best technical analysis. To the extent that it is possible, we should work to anticipate and avoid risks rather than try to manage or clean them up after the fact. The central mission of the Center for the Study and Improvement of Regulation is to refine and promote strategies to achieve these goals. Details of the Center's activities can be found on the web at http://www.epp.cmu.edu/csir/ .

As noted above, one of the best ways to get a sense of the kind of research done in EPP is to look at the topics being addressed in Ph.D. theses. We conclude this overview by summarizing three.

Three Recent Ph.D. Theses

Jim Corbett (1999; Corbett and Fischbeck, 1997) completed a thesis on "Pollution and Environmental Impacts of International Maritime Transportation" which examined the global distribution of ship propulsion emissions and possible strategies for their control. Air emissions from ships were found to be significant at global, regional and local scales. A geographically resolved global inventory of emissions from commercial ship engines operating internationally was developed. Global annual NOx and SOx emissions from ships were found to be 3.08 Tg (1012 grams) as N, and 4.24 Tg as S, respectively, more than 14 percent of nitrogen emissions from global fuel combustion sources and more than 16 percent of sulfur emissions from world petroleum use. Moreover, nearly 70% of ship emissions occur within 400 km of land regions, and 85% occur north of the equator. The work included development of a national inventory of emissions from commercial ships operating in U.S. waters, which indicated that emissions from ships on U.S. inland rivers equal about 70% of the emissions from ships on all three U.S. coastlines combined. On the coastlines, oceangoing vessels account for most of the commercial ship emissions.

Ship sulfur emissions were included in a global chemical transport model to quantify the contribution of these ship emissions on ambient concentrations of sulfur dioxide and sulfate in the marine environment and in coastal regions. By applying the emissions data set for SO_2 and PM emissions from ships within a global chemical transport model, Corbett concludes that the impact of ship emissions is significant on SO_2 and sulfate concentrations, and on global indirect radiative forcing. The impacts of proposed regulations to control emissions from new engines were evaluated, with the conclusion that existing marine engines should be considered if air quality objectives are to be met within the next twenty years. Engineering technologies that can be feasibly retrofit on existing engines were identified and their life-cycle costs estimated. An assessment of policy strategies for reducing emissions from ships was developed.

Another recent thesis, by John Chung-I Chuang (1999; Chuang and Sirbu, 1999), addressed the problem of "Economies of scale in Information Dissemination Over the Internet." This dissertation examined several different levels and dimensions along which economies of scale savings may be realized. At the information product level, economies of scale savings may be realized along the object, consumer and temporal dimensions through strategies such as information bundling, site licensing and subscriptions. At the information transport level, economies of scale savings may be realized through just-in-time delivery, multicast, network caching and replication strategies. Each of these strategies was studied. Along the object dimension, a multi-product bundling model with multi-dimensional consumer taste characteristics was developed to study the optimal bundling and pricing strategy of information goods such as academic journals. Using empirical journal usage data and cost projections for information-delivery over the Internet, the model finds that metered usage (i.e., articles-on-demand) should account for a significant fraction of revenue when articles and subscriptions are optimally priced according to a mixed bundling strategy. Along the receiver dimension, a communication cost model for multicast was developed. The model demonstrated that multicast group size could serve as an excellent proxy for multicast tree cost. Computer simulations showed that, statistically, multicast tree length grows at the 0.8 power of the multicast group size until the point of tree saturation, beyond which additional receivers can be added to the group without further tree growth. This suggests that a two-part tariff may be appropriate if providers choose to adopt a cost-based approach to multicast pricing. Along the temporal dimension, economies of scale savings can be realized through network caching and replication. The thesis offers a vision of, and motivation for, a distributed network storage infrastructure with service guarantees. Caching and replication can be treated as different service classes within a unified quality-of-service framework. Key components of the distributed network storage architecture include: service specification, resource reservation, resource mapping, admission control, real-time resource management and pricing. After establishing a research roadmap, the thesis focused on the resource mapping problem and developed a formal mapping model, allowing services with different traffic profiles and performance specifications to be mapped into an optimal combination of storage and transmission resources.

A third thesis completed in recent months was by Daniel Teitelbaum (1998; Teitelbaum & Dowlatabadi, 2000) on the topic "Intelligent agents for the study of technological change and pollution control." The factors which speed and slow technological innovation have been of interest to policy makers since at least the mid 1960's. Since that time, many theoretical models of innovation at the firm level and at the industry level have been proposed. Due to limitations in computational complexity, nearly all of these models have assumed a single, representative firm type. Very few have systematically investigated the implications of markets with a variety of firm types. With increases in computing power and the advent of agent-based modeling, interactions between agent types can now be explored. In this thesis, a computational model of innovative firms in competitive markets was developed and presented. Firms devote resources to R&D that can lead to new, improved products, allowing firms to steal market share from their competitors. Initially, two types of firms, differentiated by the strategies they use in pursuing new innovations, are allowed to coexist. One type pursues exclusively radical innovations, while the other pursues exclusively incremental innovations. The thesis demonstrated that under reasonably realistic conditions, a synergy exists between firms of different types, which allows heterogeneous populations of firms to earn more than homogeneous ones. In a latter stage of the work, firms capable of making optimal decisions were added. Pollution and a government that monitors, taxes and limits pollution were also added. It was found that the model agrees qualitatively with established results from the economics of pollution control literature. In addition the thesis shown that, in this model world, government can control pollution more effectively when firms are given time to prepare for the onset of pollution regulations rather than being surprised by them. Finally, an endogenous pollution regulation mechanism was proposed. The results showed that the effects of pollution controls could vary widely across firm types.

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