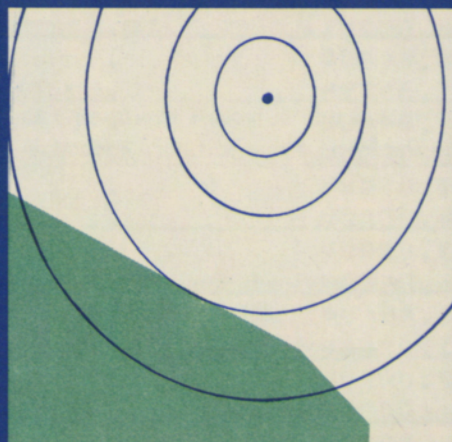
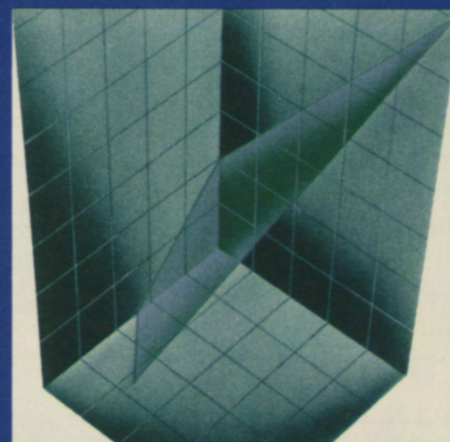
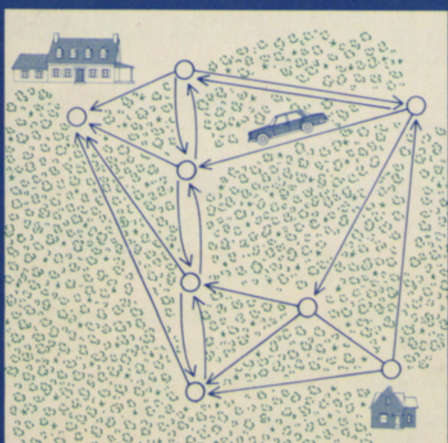
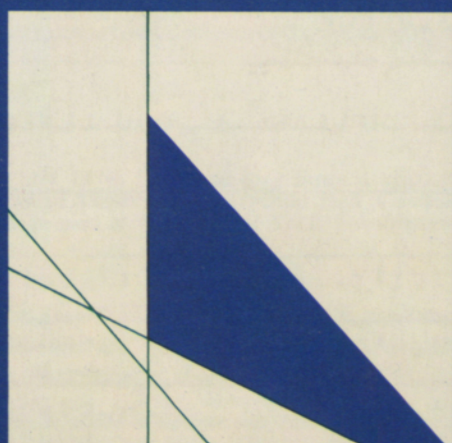
# ENGINEERING

## CORNELL QUARTERLY









VOLUME 13
NUMBER 1
JULY 1978

## OPERATIONS RESEARCH COMES OF AGE

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| 37 | Y4 | BS | 2.21799 | 3.00000 | . | NONE |

# IN THIS ISSUE



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*Outside front cover illustrations, clockwise: a graphical representation of a nonlinear program; a geometrical representation of a two-person zero-sum game; a graphical representation of a linear program; a diagram illustrating a shortest-route problem.*

*Opposite: Computer program print-out from a student operations research project.*

# OPERATIONS RESEARCH

*by George L. Nemhauser*

In 1961 I received a Ph.D. in operations research and joined the faculty of The Johns Hopkins University. Not very many people had heard of operations research then. I recall several cocktail conversations with dialogue like this:

I: I teach at Johns Hopkins.
She: How interesting; in what field?
I: Operations research.
She: It must be fascinating to be a surgeon.

At that time and place, this response was understandable. Johns Hopkins is especially well known for its medical school (as well as for its second-place lacrosse team), and the name operations research is not descriptive of the field. Other names like systems analysis, industrial engineering, and management science are also unsatisfactory—equally undescriptive, too narrow, or with misleading historical connotations.

The recognition of operations research has surely improved to the extent that confusion with medicine is no longer a problem. I still feel, however, that not many people know much about operations research, and I have yet to find a short definition that can see me easily through the cocktail circuit. My preference is to say that we in operations research work on problems concerning the management of resources —people, materials, machines—of private and public organizations. By management I mean both short-term control and long-term planning. Operations research is a *quantitative* approach to these decision-making problems in complex systems. The systems generally have many interrelated parts, some of which may behave randomly.

## DECISION MAKING AND MATHEMATICAL MODELS

An operations research study involves the construction of a *model,* which is generally a mathematical representation of an idealized version of a system. The model is supposed to describe, approximately, the behavior of the system.

The feature that distinguishes operations research from other approaches to management problems is its quantitative approach and reliance on mathematical models. Thus operations research studies have an inherent scientific objectivity that is both an asset and a limitation: although the ability to formulate a problem logically and precisely is an advantage, there are many problems that can be quantified only in part or not at all. The feature that distinguishes operations research models from traditional mathematical models used in the physical sciences and engineering is their emphasis on *decision making.* An operations research model generally incorporates many possible choices and criteria that measure the performance of the system relative to these options. Performance is frequently measured in economic terms.

The construction of a mathematical model involves compromises between accuracy and tractability. A model must capture the salient features of a problem, yet it must be simple enough to manipulate analytically, numerically, or statistically. When an operations research study does not succeed, frequently the reason is that the model is not an adequate representation of the real problem. The part of the real problem that could be handled quantitatively might have been a trivial part of

*"... a quantitative approach to ... decision-making problems in complex systems."*

the total situation or a nontrivial part that was mistakenly assumed to be the whole problem.

In the latter situation, operations research can still be very useful so long as it is recognized that guidelines rather than answers are provided, or that the answers provided are in response to "what if?" kinds of questions. The considerable amount of operations research work that is now going on in the energy sector is an example. I am optimistic about the ability of current models to provide useful guidelines regarding oil production and consumption under assumptions about OPEC policy. I would be dubious, however, about quantitative models that supposedly predict OPEC policy.

Some argue that applied operations research should be judged according to whether the solution has been implemented. This straightforward kind of evaluation may be appropriate in the private sector, but in the public sector we may have to settle for less objectivity and require only that the work influence the decision process.

For example, I once constructed a model for the problem of dividing a state into Congressional districts. The work was in response to the Supreme Court decision that declared unconstitutional those state laws that created districts without reference to the "one man, one vote" principle. The court, of course, recognized that "one man, one vote" does not mean that every Congressional district must contain exactly the same population. Even though it would be theoretically possible to achieve almost exact equality of representation, such redistricting would be impractical and would be dominated by geographical, social, and political constraints. The model I devised could minimize population differences among districts in accordance with certain well-defined geographical and social constraints. It could not, however, anticipate many other necessary political considerations. The model represented the ideal case with respect to the legal criteria for districting, and could be used by the courts for purposes of comparison with politically realistic plans. Also, it could provide many alternative possibilities that could form the basis of negotiation among the interested parties.

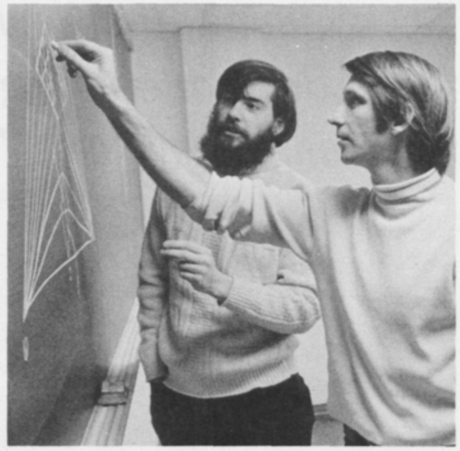
Although I cannot overemphasize the importance of model building, not very much is known about the process itself. To a great extent, modeling is an intuitive process and an art. We teach it largely by example and we learn it by doing it and studying our mistakes as well as our successes.

Models are analyzed or solved with mathematical techniques and computers. More powerful techniques enable us to work with more complex and realistic models. The fields of mathematics most commonly associated with operations research are probability, statistics, and optimization. Probability and statistics are obviously important because of the random behavior of systems and the random samples that are used in producing data for the models. Optimization techniques are the formal methods used to determine decisions that maximize performance. Computers are needed, of course, to handle the large amount of data that is required and the extensive computations that are involved in the analysis of complex models. In principle, the

*Research and teaching are the complementary aspects of Cornell faculty activity in OR and IE, as in all engineering fields.*

*Right: Professors with common research interests frequently confer on specific problems. Michael J. Todd (at left) and Leslie E. Trotter are specialists in combinatorial optimization.*

*Below: Students work closely with professors in graduate courses. Here Howard M. Taylor 3d discusses problems in applied probability with class members.*



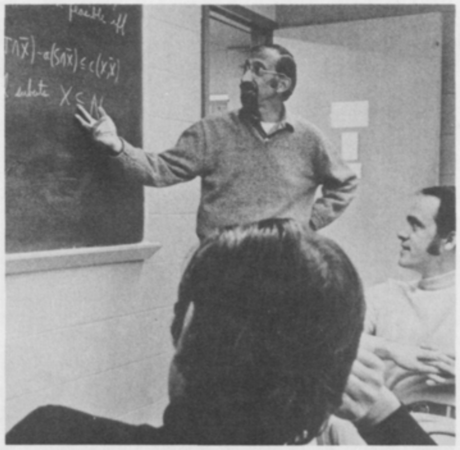
approaches and methodology of operations research could have been conceived without computers, but in reality, the field would not have succeeded without them. The computer has had an enormous influence and will continue to do so. The current boom in time-shared computers and the new rapid developments in minicomputers have made computers and, consequently, sophisticated mathematical methods, accessible in many new environments.

The viability of operations research as a field depends on the robustness and flexibility of the models and techniques. It is essential that a small number of prototype models and techniques be applicable, with only small modifications, to a much larger number of problems. Fortunately, this is the case. For example, the political districting model that I have discussed is conceptually a general model for dividing a geographical area into regions. The methodology developed for the political districting problem has been used by the police department of a large city to divide the city into "patrol car" regions. There have been several other applications of this methodology.

In the early stages of operations research, techniques were developed in response to problems and models that required solution, and many of these techniques, such as linear programming, have become standard tools routinely used in government and industry. Thus it is misleading to think of operations research as an esoteric subject. The practice of operations research can be considered a branch of engineering whose scientific base is mathematics and economics; sometimes this is called systems or modern industrial engineering. Since most of the applications occur in the business environment, it is also natural to think of operations research as science applied to management, and for this reason one sees in some universities a competition between the business and engineering schools for the development of operations research. Although either place can provide a natural home, I prefer engineering because of its stronger mathematical tradition.

Advances in operations research come from the development of new theory and methodology, and from the identification of new applications. The methodology has become so sophisticated that methodological researchers can be experts only in narrow areas, and this specialization has created a dichotomy between the problem solvers and the theoreticians. Cornell is recognized as having one of the finest theoretical and methodological research groups in the world. We are proud of this scholarly achievement, but we worry about losing touch with reality. Since our educational function is to train both researchers and practitioners—in numbers, mainly the latter—we try to maintain a balance between theory and practice.

Projects sponsored by government and industrial organizations are an effective means of providing practical experience for students and faculty members. Such projects are an integral component of our Master of Engineering degree program (see the article by Professors Muckstadt and Schruben in this issue). Students work on a real problem, individually or in small groups, under the supervision of a faculty member, and must formulate the problem, gather data, propose a solution, and present oral and written reports on the work to the sponsor. Because of the enthusiasm of sponsors and the interest of students, project work is being expanded in our programs. We intend to involve some Ph.D. students in projects, and expect that this exposure will encourage dissertations motivated by real problems. This should enhance our applied research program and complement the highly successful theoretical component of our Ph.D. program.



*One of Cornell's outstanding faculty members in operations research was the late D. Ray Fulkerson, whose pioneer research on network flows and optimization is cited by Professor Nemhauser in this article. Fulkerson joined the Cornell faculty in 1971 after twenty years with the Rand Corporation. He died in 1976.*

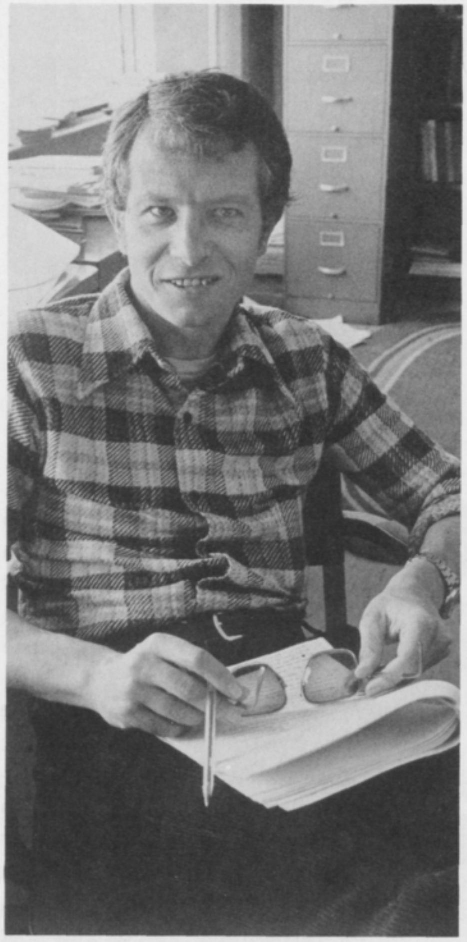
The vitality of our research program depends on the ability of our faculty to generate new ideas and problems. Two new areas in which we have recently become involved indicate the breadth of the program and, perhaps, its future directions.

One of these areas is *time-variable pricing,* which is a way to smooth out demand that would otherwise have undesirable fluctuations. For example, to smooth out the daily demand for energy, dishwashers could contain timers that would allow them to be run during the night when the per unit cost of energy would be cheaper. How should these time variables be set? Some of our faculty members have used game theory to answer this question in a different context. Cornell has a WATS telephone system that must be paid for by its users. We have developed a pricing method that allocates cost according to the value of the time period, as measured by demand: calls placed at peak hours cost significantly more than those placed during periods of low demand. Since these prices may change the utilization, the method is capable of periodically adjusting the prices until an equilibrium is reached. The method is currently being evaluated on the WATS system and we are optimistic about its usefulness in other applications as well.

Another new area of concentration at our School is the application of *network optimization* techniques to materials handling problems. Network optimization models deal with problems such as minimizing the cost of product distribution from plants to warehouses or maximizing the flow of materials in a pipeline or road network. D. Ray Fulkerson, the late Maxwell Upson Professor of Engineering at Cornell, developed much of the basic theory and methodology of network optimization. Network models have been applied successfully in a variety of situations, but not until recently to the classic industrial engineering problem of how to manage the flow of materials in a factory; some of our faculty members are doing this work. This materials flow and handling problem requires a much more microscopic model than the standard product-distribution problem and, because of the discreteness and heterogeneity of flows (for example, with the use of conveyor belts and fork-lift trucks), requires a much more elaborate model than pipeline flow. In fact, a reasonable representation of a materials handling system can require a network with tens of thousands of junction points. Recent developments in network flow methodology have made it possible to analyze networks of this size.

The future of our program is very bright. In most areas, employment opportunities for our students have never been better, and very attractive salary offers reflect the high demand for graduates at all levels. The one exception to this favorable situation is that academic opportunities for Ph.D. graduates have declined relative to those in industry and in research laboratories. Although the success our Ph.D.s are having in finding nonacademic jobs at salaries significantly higher than academic ones speaks very well for the acceptance of our program, it forebodes a worrisome problem. The growth in nonacademic demand for Ph.D.s, together with the financial difficulties of the universities, have created a growing gap between academic and nonacademic salaries, and this makes it difficult for universities to attract and keep the most talented people.

Throughout its history, though, the Cornell program in operations research and industrial engineering has shown a capacity to adapt to changing circumstances, encompass new techniques, and provide leadership in the development of the discipline. We expect to maintain this excellence.



*George L. Nemhauser was named director of the School of Operations Research and Industrial Engineering at Cornell last fall. A specialist in mathematical programming, he has been at the University as a full professor since 1969.*

*He holds the B.Ch.E. degree from the City College of New York and the M.S. and Ph.D. (granted in 1961) from Northwestern University. Prior to his appointment to the Cornell faculty, he taught for eight years at The Johns Hopkins University, where he was named outstanding teacher three times.*

*In 1963–64 he was a visiting lecturer at the University of Leeds in England, and in 1969–70 he was a National Science Foundation senior faculty fellow at the University of Louvain in Belgium. He returned to Louvain as research director of the Center for Operations Research and Econometrics for two years just before becoming director of the School here.*

*Nemhauser is an author of two texts on programming and has published widely in professional journals. He is editor of* Operations Research *and on the editorial boards of two other journals. He is a member of the advisory committee to the engineering division of the National Science Foundation, has served on the council of the Operations Research Society of America, and is a member of several other professional societies.*

# A WAR BABY COMES OF AGE

## The Story of Operations Research at Cornell

*by Andrew Schultz, Jr.*

It began during the second World War to help in the planning of military operations. It soon spread to industry. And it developed along with mathematical modeling and the digital computer. It is *operations research,* an approach to decision making that has become a part of an established engineering discipline.

At Cornell efforts to build an educational program utilizing operations research concepts began more than a quarter of a century ago. Today the School of Operations Research and Industrial Engineering is one of the major divisions of the University's College of Engineering, and the graduate Field of Operations Research is growing in size and scope. This is an appropriate time to appraise our program and consider some continuing problems in the evolution of the activity.

### THE ORIGIN AND BACKGROUND OF OPERATIONS RESEARCH

The term operations research, often referred to as OR, originated during the war when the British set up groups to study certain difficult military operations, such as the use of radar. These groups proliferated organizationally and in scope as they demonstrated the value of the activities. There emerged a realization that OR approaches could be applied to the study of any complex operation, and the term became generally accepted to mean the study of operations for the purpose of providing a better basis for decision making through the use of measured predictability. People in a variety of fields became involved in OR, and among some of them a certain degree of professional self-awareness developed.

There was at that time no established academic discipline directed to the peculiar mix of topics and techniques that constituted operations research, but its foundations had been laid. Efforts to promote "scientific management" in industry had been initiated more than seventy-five years ago by Frederick Taylor and others. Indeed, a program devoted to the decision problems of operations design and management has been in existence at Cornell for seventy-five years. (The lineage of its leadership runs from Dexter S. Kimball through John Bangs, Harry Loberg, Andrew Schultz, Jr., Byron W. Saunders, and Robert E. Bechhofer, to the present director of the School, George Nemhauser.) Some of the OR techniques developed in Britain were, in fact, direct applications of standard concepts taught at Cornell and other institutions. Others were direct applications of statistics as that discipline developed—and as it was taught here.

Nomenclature has always been difficult. As early as 1931, Cornell established within the mechanical engineering school a program called administrative engineering, and some twenty or twenty-five other academic institutions followed suit. Industry began to use the term in a more restricted sense, however, and from 1951 to 1965 Cornell used no title for the program, though the name of the department was changed to Industrial and Engineering Administration. Cornell's current designation of Operations Research and Industrial Engineering reflects recognition of the incorporation of techniques more readily identified as operations research than as engineering.

*An early leader in the development of Cornell's OR and IE program was John R. Bangs, Jr., who headed the Department of Administrative Engineering that was formed in the early 1930's. According to Professor Schultz, who worked with him during the pre-World War II years, Bangs developed a curriculum that "foresaw the quantitative approach to operational problems. It included what was probably the first course in industrial marketing (taught by Harry Loberg, who later became head of the department) and early courses in applied statistics, quality control, and human relations." Bangs, now retired, was at Cornell until 1945.*

Bangs

Probably the chief reason for the emergence of operations research as an entity was the advent of the computer and the introduction of new mathematical modeling techniques, both war-related developments. The automatic digital computer made feasible the use of statistical and other analytical techniques that were otherwise of limited practical value and also, perhaps more importantly, opened the possibility of experimentation by computer simulation. The refinement of mathematical methods for constructing abstract models was the other development with direct applicability to the analysis of production and management problems. These tools provided a firm and rigorous analytical foundation on which to build theoretical approaches to problems that previously could be dealt with only empirically.

## ESTABLISHING A NEW ACADEMIC DISCIPLINE

The potential of these new techniques was too great to ignore; the need to establish academic programs in operations research became apparent.

The first step was to formulate a curriculum. The second was to assemble a faculty. Few individuals were prepared to function in a university operations research department, partly because of the novelty and dynamic nature of the subjects involved, and an initial faculty had to be recruited or reeducated. The third step was to educate faculty members capable of advancing the unique topics that would make the new field progress. The need was great, the potential was clear, and the educational challenge was significant.

In October, 1954, seventeen individuals from nine educational institutions and four OR organizations came to Ithaca for a symposium on education for operations research. Two days of discussion, often heated, produced a number of agreements and demonstrated, at least in retrospect, considerable foresight. Clearly foreseen was the distinction between the practitioner and the researcher and, as a result, a potential educational dichotomy. The curriculum was seen as one that required considerable mathematics, but mathematics of a specialized sort not available in an organized way in existing courses; the OR courses that have evolved across the nation seem consistent with this requirement. A more difficult educational problem recognized by the delegates was the need for something analogous to laboratory and experimental work to develop skills in operational experiments, model design, decision-making-system analysis, and model testing. The need to rationalize and formalize programs to develop such competence was emphasized, as was the skill required to reconcile abstract theory with reality in an educational environment.

Much of the discussion focused on advanced education for the Ph.D., in recognition of the need for teachers and for individuals capable of doing the required fundamental research on techniques. The hope was to obtain a satisfactory balance between those prepared for practice and the smaller number of specialists needed for basic research. It was concluded that the most urgent need for the immediate future was to begin programs at the bachelor's and master's degree levels, so as to meet the forecast demand for well educated operations analysts.

In the ensuing years, progress has been remarkable and the educational programs have functioned well. A major factor in the introduction of any new technology is the "cultural lag" associated with the change. For example, the mathematical foundation and the proven techniques for statistical quality control and acceptance sampling were fully developed and published by Dr. Walter Shewhart and his colleagues at the Bell Telephone Laboratories by 1928; yet, even with the full support and pressure of the Federal government during World War II, it was more

**GRADUATE DEGREES GRANTED BY CORNELL IN INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH**

*These degrees were granted by the School of Operations Research and Industrial Engineering and its predecessor department. Years end in June. To avoid double counting, master's degree recipients who continued and obtained doctorates are omitted in the figures.*

| | 1950–54 | 1955–59 | 1960–64 | 1965–69 | 1970–74 | 1975–78* | Totals |
|---|---|---|---|---|---|---|---|
| Ph.D. | 1 | 3 | 6 | 20 | 25 | 30 | 85 |
| M.S. | 3 | 13 | 16 | 38 | 43 | 39 | 152 |
| M.Eng. | 7 | 0 | 8 | 71 | 54 | 83 | 223 |

*Note that these figures are for a four-year rather than a five-year period. The figures for 1978 are estimates.

than twenty-five years before the techniques were being voluntarily and broadly utilized in this country. One can surmise that this utilization occurred only after students who had taken courses in these subjects graduated and assumed positions of responsibility. The effective use of the computer followed a similar path.

In addition to the emergence of educational programs, several other developments accelerated the process of acceptance and utilization of OR concepts. One was the movement of the graduate business schools of the nation to apply quantitative approaches to the problems of business, a movement based on recognition of the power of the computer and of OR techniques. Studies by the Ford and Carnegie Foundations accelerated this trend. A second factor was the tremendous growth of technical and professional societies in areas related to OR. The Operations Research Society of America, the Institute of Management Sciences, and the American Institute of Industrial Engineers now have a total of about thirty thousand members. These organizations serve to orient and indoctrinate thousands of professionals and technicians and, as in any dynamically developing field, create or expose tensions between practice and educational activities. These tensions—between theory and application, academic institution and industry, scientist and engineer, research and design—are the source of articles, symposia, and technical meetings which have the effect of helping to achieve a beneficial balance.

## ACHIEVING BALANCE IN A UNIVERSITY PROGRAM

It is incumbent upon educational institutions to strive for a suitable balance. Too heavy an emphasis on research, theory, and related advanced education can lead to neglect of the education of the practitioner, loss of relevance and quality in applied courses, lack of attractiveness to students, and lack of vitality in the research program. (The prototype of irrelevance is the professor who is in a "rut.") On the other hand, concentration on the education of the practitioner to the neglect of fundamental research leads to obsolescence of both faculty and courses, low-quality education, and, ultimately, decay of the discipline. A healthy balance is fostered by an educational program that maintains a core of doctoral students preparing for careers in research or teaching, a larger number of master's degree candidates intending to enter practice, and many more students at the baccalaureate level acquiring a basic foundation in operations research theory and techniques.

Cornell's record, as the table shows, has not been inconsistent with these views of the development of the field. During the overall period from 1950 to 1978, a total of 85 Ph.D. and 375 M.S. and M.Eng. degrees were awarded. And since 1965, when the graduates of the School's undergraduate program were first identified by field, 895 baccalaureate degrees have been granted.

The numbers and subsequent activities of the doctoral graduates illustrate both the growth of the discipline and the development anticipated by the 1954 symposium on OR education. In the five-year period between 1955 and

*"There emerged a realization that OR approaches could be applied to the study of any complex operation."*

1959, three Ph.D. degrees were awarded; all three recipients are currently full professors at different institutions, and two of them head OR-type programs. During the ensuing five years, six more Ph.D. degrees were awarded; all these recipients became professors, and three are heading OR-type programs. In the next five-year period, 1965 to 1969, twenty Ph.D. degrees were awarded; while the large majority of these graduates are employed in educational institutions, a number are in industrial or consulting OR groups. Over the five-year period ending in 1977, only 50 percent of the doctoral graduates went into teaching; 41 percent took employment in institutes or laboratories doing operations research, and 9 percent are members of industrial groups.

Those who received B.S. degrees frequently elected graduate study at Cornell or elsewhere in industrial engineering and operations research, in business or public administration, or in other disciplines. Those baccalaureate degree holders who go on to obtain the M.Eng. or a similar master's degree in the general area, and those who go directly to work, become the practitioners in the field.

The responses to a survey questionnaire sent out several years ago to graduates of five undergraduate classes indicate the kinds of activity in which these individuals are engaged. As might be surmised, a minority obtained advanced degrees in law or Ph.D. degrees elsewhere (those who entered the Cornell doctoral program in operations research were not included in the survey). Of the remaining respondents, 60 percent of those who graduated between 1966 and 1973 are currently em-

Saunders

*Former heads of Cornell's OR and IE school are Byron W. Saunders and Robert E. Bechhofer.*

*Saunders headed the Department of Industrial Engineering and Operations Research from 1963 to 1967, when he became director of the newly formed School. He served until 1975, when he was elected dean of the University faculty. Currently on sabbatic leave, he plans to retire next year.*

*Bechhofer, who had headed the Department of Operations Research for eight years, became director of the present School when this was reorganized in 1975.*

Bechhofer

ployed in areas in which they are capitalizing directly on their education in computing and applied operations research techniques. Half of these are in OR groups in industry, in consulting firms, or (a few) in government; one-third are engaged in computing or data-processing activities; and the balance are in finance. An analysis of the kind of work these graduates are doing shows that 30 percent hold line functional responsibilities—more often in marketing than in production or finance—in industrial firms; the balance are self-employed or hold general management positions.

## EFFECTIVENESS OF OR/IE EDUCATION AT CORNELL

In the past twenty-five years, Cornell has succeeded in building a superior educational program in industrial engineering and operations research that has been well balanced and appropriate to the needs of the times. In future years, as OR concepts become more widely understood and accepted, and as the use of the computer becomes even more pervasive, opportunities for OR specialists will be available on a greatly enlarged scale. The demands for competent practitioners should grow, and much of the educational thrust must be directed to meeting this need.

How will this affect the educational program at Cornell's School of Operations Research and Industrial Engineering? First, more faculty members will be needed in order to maintain the vitality of the program as the scale of OR activity rises in business, industry, and government. Second, the format and content of educational programs will need to be adapted so as to respond to the strong groundswell of sentiment, expressed in the journals of the professional groups, for more emphasis on applied aspects of the field. Third, care must be taken to ensure the maintenance of quality programs of research and advanced studies that are responsive to the needs of the field as it develops.

In its relatively brief history, the field of operations research has experienced remarkable growth and change, and educational institutions have had to be both responsive and anticipatory. The second quarter century, like the first, offers opportunity and challenge to OR specialists in the universities, as in practice.

*Schultz*

*Andrew Schultz, Jr., a Cornell engineering graduate, former dean of the College of Engineering, and professor of operations research and industrial engineering, writes about the academic program in that field from the vantage of long experience as student, teacher, and administrator.*

*He joined the Cornell faculty in 1941 after completing his bachelor's degree in 1936 and then his doctorate. During World War II he served in the Army as chief of section in the Industrial Service, Ammunition Division, Office of the Chief of Ordnance, and attained the rank of lieutenant colonel. After the war he returned to the University as a member of the industrial engineering and administration faculty, and in 1951 began a twelve-year term as head of that department. He was dean of the College from 1963 to 1972.*

*Since July 1, Schultz has been serving as acting dean of the College while a new dean is being selected. (Edmund T. Cranch, who succeeded Schultz as dean in 1972, recently became president of Worcester Polytechnic Institute.)*

*A specialist in operations analysis, Schultz has been active throughout his career as an industrial consultant, and serves on the boards of several firms. In 1962–63 he spent a sabbatic leave as vice president and director of research for the Logistics Management Institute in Washington, D.C., and during earlier leaves he served as an operations analyst for the Operations Research Office of The Johns Hopkins University and as consultant to the Engineering Advisory Committee of the Western Electric Company at its Engineering Research Center in Princeton, New Jersey. He also served for a number of years as chairman of the National Institutes of Health study section on accident prevention.*

*During his years as dean, Schultz was active at the national level in developing the professional status of engineering, particularly as a board member of the Engineers Council for Professional Development and as a member of the Commission on Education of the National Academy of Engineering.*

*He is a fellow of the American Institute of Industrial Engineers and the American Association for the Advancement of Science, and a member of the American Society for Engineering Education, the Institute of Management Science, the Operations Research Society of America, and the honorary societies Sigma Xi, Tau Beta Pi, and Pi Tau Sigma.*

# INTERFACING WITH INDUSTRY

*by John A. Muckstadt and Lee W. Schruben*

A manufacturing company saves a million dollars a year by making more effective use of a braze oven. More efficient scheduling for an operating room enables a hospital to cut costs and give patients better service. The Navy speeds up aircraft repair by keeping spare engines where they are most likely to be needed.

These are among the concrete benefits that could result from projects conducted by Master of Engineering students at Cornell's School of Operations Research and Industrial Engineering. They demonstrate not only the effectiveness and wide applicability of OR methods, but also the possibilities of a vital educational program.

In recent years the School has strengthened its ties with industrial and other working organizations in recognition of the fact that such contact is crucial for a teaching and research program in a field that is changing rapidly in scope, content, and function. OR techniques, first developed in response to military and then manufacturing problems, are now being adapted by service and public institutions as well, in areas such as transportation system design, health care delivery, financial planning, and corporate management. A good university program needs to foster the extension of ideas and techniques and at the same time keep in touch with applications in the "real world."

## THE M.ENG. PROGRAM AS A COOPERATIVE VENTURE

Contact between the School and outside organizations (manufacturing firms, businesses, hospitals, government agencies, etc.) is made through faculty consulting activities and undergraduate field studies as well as through the Master of Engineering program; but the project work for this professional degree has become the major interface.

In this program, the main purpose is to prepare students for careers as practicing engineers. For their required project, they work individually or in small groups to carry out a thorough and practical analysis of a concrete problem. The outside organizations sponsor specific projects, which are carried out under the cooperative guidance of Cornell faculty members and practitioners from the sponsoring groups.

What kinds of problems are appropriate and how are they handled? The most meaningful and successful projects begin with a concrete situation to investigate, require the collection and analysis of data, involve contact between the students and the operating personnel, offer opportunity for applying knowledge learned in courses, and are suitably limited in scope and duration. Students carry out all phases of the project, from writing the proposal to presenting recommendations; the final report satisfies an academic requirement, but is directed to and written for the sponsor. Because the objective is inherently educational, the students are encouraged to be creative and to analyze, question, interpret, and suggest.

Participation in such a project clearly benefits students preparing for professional work. They undergo a form of apprenticeship, gaining experience and confidence, learning what not to do as well as what to do, applying analytical and quantitative skills learned in formal

*A company that manufactures equipment for materials handling is the sponsor of a project for Master of Engineering students in operations research and industrial engineering. Students Don Peskin (at left) and Bill Russman (at right) confer with controller Bill Lynn at the Raymond Manufacturing Company in Greene, New York, about their use of statistical analysis techniques to forecast demand for the company's eight product lines. Professor Schruben is the faculty adviser.*

studies. The opportunity to work with and observe experienced practicing professionals is invaluable. The faculty advisers also benefit from observing operations research and industrial engineering in practice. Involvement in project work is likely to give professors new perspectives and to have a significant impact on their teaching and research.

From the point of view of the sponsor, the project analysis and recommendations are obviously of direct value. The project report and such supplementary materials as computer programs can serve as a basis for action or for further study. In some cases, the student project members can help implement recommended solutions, or accomplish tasks that could not otherwise be undertaken because of the sponsor's limited resources. Also, the project group can serve as a conduit for the early transfer of relevant new methods and principles to the sponsor. Working from a different vantage point and under different constraints than in-house personnel, project members may contribute novel insights into the situation. The joint venture also provides the sponsor a means of developing ties to a first-rank school in a distinguished university; opportunities for further interaction include, for example, special lectures and faculty consulting.

## MATERIAL CONTROL SYSTEMS AS A CORNELL SPECIALTY

One developing area of operations research in which Cornell is able to make a significant contribution is that of material control systems, an aspect of modern manufacturing that promises to fundamentally change the way industries are run. New approaches to inventory control, material processing, production scheduling, and warehous-

# Some Recent Master of Engineering Degree Projects

## 1 AN OPERATING-ROOM SCHEDULING PROBLEM

Officials at the New York Hospital requested a procedure for operating-room scheduling that would increase utilization of the operating-room suite and reduce personnel overtime. In the project analysis, the system was examined in terms of queuing models, job sequencing algorithms, statistical prediction techniques, and regression analysis. It was necessary to predict accurately the lengths of surgical procedures as a basis for determining the optimal sequencing policy. The interaction of the operating room with other areas of the hospital was also studied. Data for several months of operation were collected and analyzed. From these observations, means and variances for various types of operations, percent of utilization, average overtime, average late time for early-morning operations, and several other statistics were computed, and an improved scheduling procedure was developed.

## 2 OPTIMUM UTILIZATION OF A FACILITY

The objective of this project was to maximize braze oven utilization for a General Motors plant. The approach was to develop a computer simulation of current operations and possible changes; the model permitted a study of the repercussions of proposed alterations without making the actual physical changes. The best simulated method changes were gradually introduced in the plant on an experimental basis, and this led to permanent changes that resulted in savings in excess of a million dollars a year.

## 3 AIDS FOR A REPAIRABLE INVENTORY SYSTEM

A critical aspect of the repair system for Naval aircraft is the availability of spare engines, but analytical models used for determining their optimal allocation require assumptions about the operation of the Navy's resupply system. In a Cornell M.Eng. project, a model named *S*imulation for the *P*erformance of *A*ircraft *E*ngine *R*epair *S*ystems (SPAERS) was developed to simulate different configurations of the Navy's aircraft carrier engine resupply system. Analysis showed that SPAERS can be used as a tool for verifying the predictions of models and for making statistical comparisons of alternative engine resupply system configurations.

## 4 DESIGN OF A MANAGEMENT INFORMATION SYSTEM

For this project, a computerized system was designed to handle the entire planning and scheduling operation for a cost department. This computerized system offers many advantages over the present manual system: It completes the process of planning and scheduling production in a matter of minutes, with much less error. It can generate a good schedule (by heuristic methods) for production, an accomplishment that is virtually impossible with use of manual techniques. It functions as a Management Information System (MIS) to keep managers informed about departmental operations and to identify and locate possible problems. Finally, the computerized system can do all of this at significantly lower cost; savings are likely to be about one thousand dollars a month.

## 5 WORK ON A RETAIL OUTLET PROBLEM

After a retail corporate engineering department had evaluated the labor savings effected by the installation of an on-line inventory reporting system, a Cornell student formulated a labor-scheduling model for the store managers. This led to an investigation of the buyers' purchasing practices and the development of a model for the purchasing system. As part of the modeling, two methods for predicting inventory movement were tested, and both gave acceptable results. An algorithm was developed to determine the best buying policy for each product; this algorithm incorporates the sales forecasts, lead times, and vendor terms, and indicates when the product should be ordered. When this algorithm was tested on a sample of products, the results indicated that a 25 percent savings in inventory holding and ordering costs could be realized.

*"The overall result . . . will be profound, bringing about what may come to be regarded as a second industrial revolution."*

ing offer opportunities to increase productivity, provide better customer service, and improve the utilization of resources. New methods include both technical advances, such as the use of minicomputers in machine control and material movement, and innovations in management science. The overall result will be profound, bringing about what may come to be regarded as a second industrial revolution.

Cornell faculty members have special interests in many aspects of material control systems and are beginning to cooperate with manufacturing firms and other organizations in mutually useful projects. In such arrangements, students under faculty supervision will conduct research on specific problems presnted by the companies. The program has the potential of expanding Cornell's research and teaching capabilities and at the same time giving the sponsors access to new methodologies as applied directly to their operations.

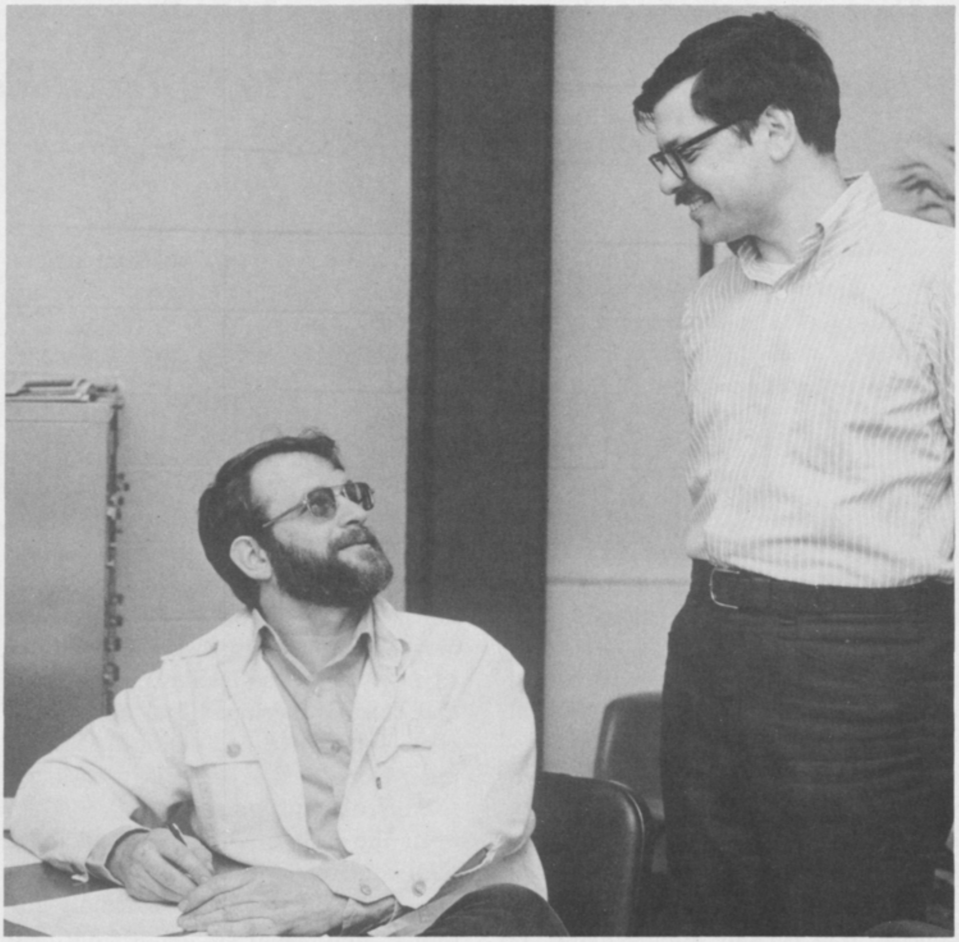
One of the areas in which Cornell faculty members and their students plan to work is the design of automated warehouse and production systems. Specific aspects include operating policies and the interaction of the warehousing system with other manufacturing functions. A major effort is planned in the area of computer software for the design of warehouse facilities; techniques that can be developed and applied include interactive computing and computer-aided design, especially with the use of computer graphics.

In the field of production planning and control, Cornell researchers are especially interested in assembly-line design, automated computer-controlled material flow, and work-in-progress inventory control. These techniques could help manufacturers alleviate production bottlenecks and shorten the time lag between prototype and production. The competitive advantage of earlier market introduction of new products is obvious.

The resolution of inventory management problems is another area of special interest at the School. For example, a company with several warehouses might wish to establish a plan for distribution and storage of stock that would give better service to customers and reduce the investment in inventory. Both faculty research and Master of Engineering project work will contribute to the development of workable and improved policies.

Cornell facilities in support of research and project work on material control systems will include a minicomputer laboratory with graphic capabilities and special laboratory equipment. In some cases, a sponsor's computer facility can be used for M.Eng. project work.

Theory and application: these are the two faces of modern operations research and industrial engineering, and too often they are addressed independently. We believe that cooperative efforts by university and professional groups, of the sort now being initiated at Cornell, will help reconcile these viewpoints. Academic research and teaching on the one hand and professional practice on the other are both essential to the continued development of the discipline, and they can and should reinforce each other.



*Professors Schruben (at left) and Muckstadt cooperate in organizing and directing project work for the M.Eng. (OR & IE) degree program. Another professor active in the program is William L. Maxwell.*

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*John A. Muckstadt and Lee W. Schruben are faculty members of Cornell's School of Operations Research and Industrial Engineering. Muckstadt, an associate professor, is a specialist in inventory and logistics control; Schruben, an assistant professor, is interested primarily in simulation and has worked in the areas of health care delivery systems and manufacturing systems.*

*Muckstadt came to Cornell in 1974 after twelve years with the Air Force, first as a faculty member in the Air Force Institute of Technology, and then as an operations reseach analyst at the Air Force Logistics Command headquarters in Dayton, Ohio. He also held a part-time teaching position at the University of Dayton.*

*He holds the A.B. degree in mathematics from the University of Rochester, and the M.S. in industrial administration, the M.A. in mathematics, and the Ph.D. in industrial engineering from the University of Michigan. At Michigan he received the 1964 Outstanding Graduate Student Award in engineering.*

*He is a member of the Operations Research Society of America, the Mathematical Association of America, and the Institute of Management Sciences. In the latter organization, he has served as an officer of the College of Real Time Systems since 1971. He is a member also of the honorary societies Sigma Xi and Alpha Pi Mu. He has served as an associate editor of various professional journals.*

*Schruben earned a Cornell undergraduate degree, with honors, in industrial engineering in 1968, and returned to the University as a faculty member in 1976. In the years between, he studied for the M.S. in statistics at the University of North Carolina and the Ph.D. from the Yale University School of Organization and Management, and served as operations research analyst for the Naval Command Systems Support Activity in Washington, D.C., and as a staff member of Operations Research, Inc., in Silver Spring, Maryland. Before joining the Cornell faculty, he spent a year at the University of Florida as associate director of the Health Systems Research Division and as assistant professor of industrial and systems engineering. He has also worked in operations research at the Emerson Electric Company in St. Louis.*

*He is a member of the Operations Research Society of America, the American Institute of Industrial Engineers, and the honoraries Tau Beta Pi, Alpha Pi Mu, and Sigma Xi.*

# DIVIDING UP THE PIE

## Help from Operations Research in Problems of Fair Distribution

*by William F. Lucas*

A mother dividing a cake among her children, a utility company setting up a rate schedule, a government assessing taxes: all are confronted with the problem of how to make a fair distribution. How should such decisions be made? Can "fairness" be determined objectively?

Fair distribution of benefits and costs is an important issue in a participatory democracy, as in a family, and one that arises frequently in decision making of all kinds. It is also a matter of concern to operations research specialists, whose job is to provide objective methods of analysis of complex systems and organizations. It is, however, an area in which traditional operations research has not yet been particularly successful.

Quantitative OR techniques have proved to be very useful in many other kinds of problems. Efficiency improvement and optimization of procedures were among the early areas of application and continue to be important. Situations that involve more than one decision maker, strategic encounters, or conflicting goals can be analyzed according to game theory. Even cases involving less tangible components, such as consumer preferences or the decision maker's personal attitudes, are handled with the use of modern utility theory. Many problems involving a substantial element of risk or uncertainty are solved with the aid of various OR theories involving concepts from probability and statistics. But what about the concept of fairness? In OR terms, the question is whether the necessary fundamental theory and practical techniques, or algorithms, can be developed to deal successfully with specific problems of allocation.

### WAYS OF ALLOCATING COSTS AND BENEFITS

The difficulties in making allocation decisions arise in establishing the criteria. Dividing a "budget pie" or distributing tasks among individuals requires guidelines beyond the avoidance of prejudice or self-interest. For example, in arriving at a method for auctioning off-shore oil leases, the Department of the Interior must weigh various factors; impartiality and the overall welfare of the country are likely to be of greater importance than maximizing income. In accepting bids for the construction of new ships, the United States Navy must by law select the lowest bidder who meets the specifications; nevertheless, the Navy also has a legitimate concern for the health of the ship-building industry.

Fairness is often defined in terms of established principles involving general notions about equality, symmetry, or interchangeability, and it is often implemented by a supposedly unbiased official, authority, or arbitrator who treats all alike. The decision maker may be a mother attempting to meet the needs and wants of her family, a judge or jury trying to arrive at a just compromise in a liability or bankruptcy case, or an administrator seeking to eliminate bias or prejudice in assigning responsibilities or determining salary increases. This approach to fairness, though it may be based upon certain standards, is essentially authoritarian.

In contrast, there are more operational procedures that allow the par-

*"Problems of equitable distribution can only become more urgent as participants ... grow more numerous, goods become scarcer, and costs rise."*

ticipants themselves to arrive at what they agree is a fair division of the goods. These schemes do not assume that the persons involved have the same preferences, nor that fairness has to be defined in terms of fundamental rules or absolute standards, or even in terms of a technical concept such as "expected value" in statistics or "a measure" in analysis. In other words, there exist methods for dividing up goods which, under reasonable assumptions, will assign each person a part that he or she has declared to be fair. Three simple examples illustrate the approach.

### EXAMPLE NUMBER 1: DIVIDING A CAKE

There is a well known way to divide a finely *divisible* commodity such as a cake or a parcel of land between *two* persons: One of the people divides the commodity into two pieces and the other makes a choice. The decision as to who will cut can be made by the flip of a coin or by some other ad hoc rule. It is assumed that either piece is acceptable to the "cutter," and that at least one satisfies the "chooser."

This scheme can be extended to *three* participants as follows. One person, denoted by 1, partitions the commodity S into three disjoint pieces, $S_1$, $S_2$, and $S_3$. Each of the remaining two participants, denoted by 2 and 3, simultaneously (or merely in ignorance of the other's choice) makes a declaration as to which of the pieces $S_1$, $S_2$, and $S_3$ are acceptable. This information can be summarized in a 3 by 3 array as indicated in Figure 1. An entry of 1 means that the indicated piece is acceptable to the corresponding player; a 0 means it is unacceptable. For example, the array in Figure 1 indicates that any one of the three pieces is acceptable to person 1; only piece $S_1$ is acceptable to 2; and either $S_1$ or $S_3$ is fair in the eyes of 3. In this case, a fair allocation is obtained by assigning $S_1$ to 2, $S_3$ to 3, and $S_2$ to 1.

*Figure 1*

| Person | $S_1$ | $S_2$ | $S_3$ |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 1 | 0 | 0 |
| 3 | 1 | 0 | 1 |

Of course, this procedure will not always give rise to a unique assignment, as in the illustration. It seems natural to impose in general the condition that any one of the three pieces is acceptable to the person who cuts and that each of the other people considers at least one of the three pieces to be a fair assignment. Even so, there may still arise cases in which a solution is not immediately evident. Suppose, for example, that person 2 and person 3 both want the same piece, as indicated in Figure 2. What can be done?

*Figure 2*

| Person | $S_1$ | $S_2$ | $S_3$ |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 1 |
| 3 | 0 | 0 | 1 |

First of all, we can assume that since 2 and 3 have both declined pieces $S_1$ and $S_2$, they have no objection if *one*

**Table 1. AN ESTATE SETTLEMENT**

| | | Alice | Bob | Carl |
|---|---|---|---|---|
| Bids for objects: |  | 40,000 | 30,000 | 41,900 |
| |  | 19,000 | 32,000 | 26,100 |
| |  | 10,000 | 13,000 | 12,100 |
| Sum of bids | | 69,000 | 75,000 | 80,100 |
| Fair share | | 23,000 | 25,000 | 26,700 |
| Objects assigned | | |   |  |
| Value of objects | | 0 | 45,000 | 41,900 |
| Cash component of share | | 23,000 | -20,000 | -15,200 |
| Share of cash surplus* | | 4,067 | 4,067 | 4,067 |
| Settlement | | 27,067 | -15,933;   | -11,133;  |

*Each share = 1/3 of the total cash surplus of 12,200 dollars.

of these pieces is assigned to 1. So let us assume that one of these pieces, say $S_2$, is assigned to 1; then 2 and 3 should be willing to follow the two-person divide-and-choose scheme with a "cutter" and a "chooser." In this case, the object to be divided consists of the sum of the remaining two pieces, $S_1$ and $S_3$.

It is not difficult to extend this procedure for three persons to a similar scheme for an arbitrary number of participants, as well as to cases in which the participants are to be awarded unequal shares of the original good.

## EXAMPLE NUMBER 2: SETTLING AN ESTATE

Suppose a family estate consists of three *indivisible* objects—a house, a summer cottage, and a luxurious automobile—and that it is to be divided in equal shares among three children—Alice, Bob, and Carl. A fair division scheme in this case would begin with each heir submitting a sealed bid on each of the three objects. Then the estate would be divided so as to ensure that each heir receives a share equivalent to at least one-third of the evaluation that he or she declared for the entire estate.

For example, let us assume that the bids, expressed in terms of dollars, are as given in Table I. From this table we see that Alice values the house at $40,000, the cottage at $19,000, and the car at $10,000. The sum of these is $69,000, which can be taken as her evaluation of the full estate; therefore, her fair share, by her own evaluation, is $23,000. Similar calculations are made on the basis of Bob's and Carl's bids. Then the objects in the estate are assigned to the respective highest bidder, appropriate side payments are made in cash, and the resulting cash surplus is divided into three equal shares of $4,067.

If a scheme like this is followed, anyone who bids honestly is *guaranteed* at least a fair share (which may consist of objects and/or a cash settlement). Of course, one can gamble and bid lower than his or her true evaluation of a desired object, or bid higher on an object that is expected to go to someone else in order to raise this individual's total evaluation and therefore the final share. However, this person then risks obtaining a final settlement that is less than his or her fair share or includes less desired components.

An assumption made in this procedure is that the value declared by each participant for the complete estate is the sum of the values of the individual objects; if this is not the case, the scheme can be modified easily so that it still provides an equitable distribution. Or the scheme can be altered to accommodate different circumstances, such as a situation in which an individual has preferences as to who should get the objects that are assigned to others: Bob may prefer to see the house go to Alice rather than to Carl, for example. Cases in which the shares are unequal, or in which there are more objects to be divided or more heirs, can also be handled easily. The value of one heir knowing another's bid beforehand, or of collusion, can be determined.

## EXAMPLE NUMBER 3: SELECTING A CHAIRPERSON

A problem of fair allocation that may seem familiar to those in university circles is the selection of a department head. Suppose a department has five tenured faculty members who have the responsibility of nominating a new chairperson from their own ranks. Four of them consider the job an onerous task and may be willing to forgo a part of their salary increments for the next year in order to be free of this responsibility. The five professors can express their preferences among all the choices in terms of dollars, as illustrated in Table II. Each row sums to zero.

*"Fair distribution of benefits and costs is an important issue ... that arises frequently in decision making of all kinds."*

The five professors are indicated by 1, 2, 3, 4, and 5. The number in row i and column j represents the amount of *additional* pay that professor i expects to receive if professor j becomes chairperson. Most entries off the main diagonal are negative, since all but professor 4 do not want the job and are usually willing to "pay" to have someone else take it. For example, the entries in row 2 indicate that professor 2 will pay $500 to have either 1 or 3 take the position, and will pay $1,000 to have his favorite, professor 5, as chairperson. On the other hand, he expects a bonus of $1,500 if he assumes the position, and furthermore he expresses his dislike for professor 4 by expecting a raise of $500 for himself if he must work under 4.

**Table II. SELECTING A CHAIRPERSON**

*The numbers in each row represent that professor's proposals for his or her own salary adjustment according to which of the five professors is selected as chairperson.*

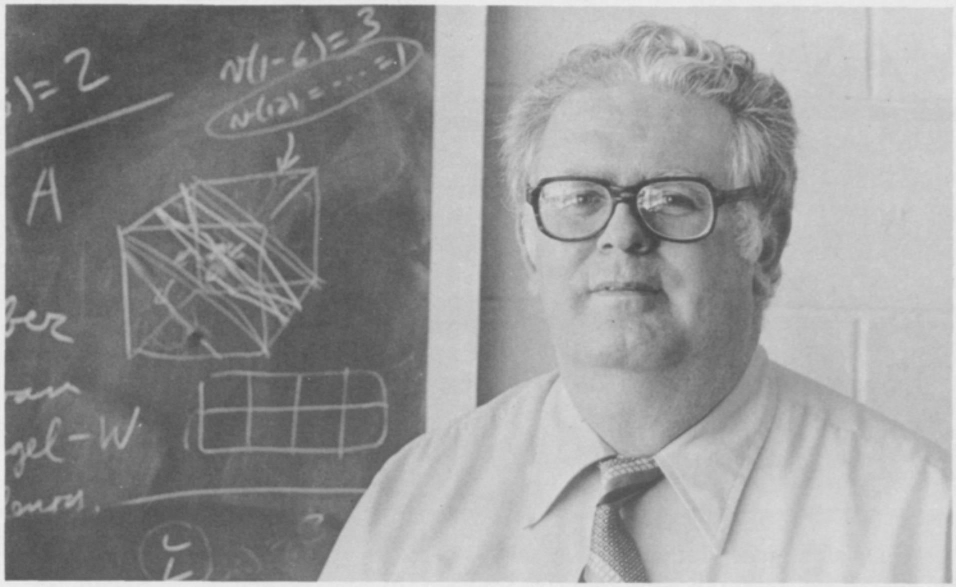
| Prof. | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 2,000 | –600 | –500 | –400 | –500 |
| 2 | –500 | 1,500 | –500 | 500 | –1,000 |
| 3 | –200 | –200 | 800 | –200 | –200 |
| 4 | 200 | 0 | 0 | –400 | 200 |
| 5 | –500 | –500 | –500 | 300 | 1,200 |
| | 1,000 | 200 | –700 | –200 | –300 |

Note that, in general, at least one column must sum to a nonpositive number. A professor corresponding to any such column can be selected chairperson, and the five salary demands expressed in this column can be met. For example, if 3 is selected, he receives an $800 bonus; 1, 2, and 5 take a $500 cut, and there is a surplus of $700 which could be distributed among the five professors. Of course, if the college dean had this information, he might retain this $700. On the other hand, it would cost the dean an additional $1,000 if he were to designate professor 1 as chairperson, while simultaneously meeting everyone's financial expectations.

## ADDRESSING REAL ALLOCATION PROBLEMS

The three simple cases I have outlined illustrate the approach that researchers are taking in meeting problems of fair allocation. Although these examples are quite trivial, they suggest how real problems with many components could be attacked. An interesting example of the solution of a real problem is the method recently worked out by members of Cornell's School of Operations Research and Industrial Engineering to set fair rates for users of the new WATS telephone system at the University; this is described in an article by Louis J. Billera, David C. Heath, and Joseph Raanan that will appear this year in the journal *Operations Research.* More complete discussions of schemes for allocation problems can be found in a forthcoming monograph of mine, *Elementary Fair Division Schemes,* and in a recent Cornell Ph.D. thesis, *On the Fair and Efficient Allocation of Indivisible Commodities,* by Richard Engelbrecht-Wiggans.

In the contemporary world, problems of equitable distribution can only become more urgent as participants—recipients, consumers, taxpayers—grow more numerous, goods become scarcer, and costs rise. The development of schemes and of algorithms for handling these problems is an area of operations research that is sure to become increasingly important in the years ahead.



*William F. Lucas, professor of applied mathematics and of operations research, is a leading expert on game theory. He came to Cornell in 1969 after several years as a mathematician with The Rand Corporation.*

*Lucas holds the B.S. and M.S. degrees in mathematics, and also the M.S. in physics, from the University of Detroit, and the Ph.D. in mathematics from the University of Michigan. After receiving his doctorate in 1963, he taught at Princeton University for two years and served as a consultant to Mathematica, Inc., a research firm in Princeton. Subsequently, he spent a year as a Fulbright grantee at the Middle East Technical University in Ankara, Turkey, where he taught economics and statistics, and then served as a visiting associate professor of mathematics at the University of Wisconsin until his RAND appointment in 1967.*

*He spent part of a recent sabbatic leave at the Leningrad Institute of Socio-Economic Problems of the Soviet Academy of Sciences as an exchange scientist sponsored by the U.S. National Academy of Sciences. Last fall he was a visiting professor of mathematics and visiting scientist for academic services at Washington State University. He has been a lecturer or director for ten summer institutes, workshops, or short courses offered for high school and college teachers and funded by the National Science Foundation. Recently he was selected to give national lecture series sponsored by the American Association for the Advancement of Science, the American Mathematical Society, the Conference Board of Mathematical Sciences, and the Mathematical Association of America.*

*At Cornell he has worked with the Center for Applied Mathematics, serving as director from 1971 to 1974. Also, he has been chairman of the policy committee of the College of Engineering and a member of the steering committee of the Peace Study Program.*

*He has published widely in his specialty field and has served on the editorial boards of several professional journals; recently he was elected scientific editor of the* International Journal of Game Theory. *He is a member of ten professional societies.*

# VANTAGE

## OR Alumni Hold Reunion

■ Ph.D. alumni of Cornell's program in operations research and industrial engineering came from all over the United States and several foreign countries to attend a 1977 reunion and conference in celebration of the twenty-fifth year of the program. Of the eighty-nine Ph.D. graduates, an impressive total of thirty-nine joined the faculty for the meeting held June 5–7. Most of the delegates appear in the picture on the opposite page.

*Identification of alumni and Cornell faculty members is given according to the numbered key shown below the picture. The names of alumni are followed by the year in which they received their doctorates and their place of employment. The names of Cornell faculty members (not italicized) are followed by their specialty fields. (A few of the delegates are both Cornell graduates and Cornell professors.) Information about the delegates was supplied by Professor Robert E. Bechhofer.*

*1. Bharat T. Doshi '74: Department of Statistics, Rutgers University. 2.* William L. Maxwell '61: scheduling, simulation. *3. Warren E. Walker '68: The Rand Corporation, Santa Monica, California. 4. Dwight E. Collins '73: Logistics Management Institute, Washington, D.C. 5. Linus E. Schrage '66: Graduate School of Business, University of Chicago.*

*6.* Byron W. Saunders: industrial systems. *7. Robert B. Rovinsky '76: Economic Research Service, U.S. Department of Agriculture. 8. Robert E. Blau '75: Member of New York Option Exchange. 9. Mark J. Eisner '70: Exxon Corporation, Florham Park, New Jersey. 10. Richard H. Bernhard '61: Department of Industrial Engineering, North Carolina State University at Raleigh.*

*11. Edward J. Ignall '66: Mathematical Methods and Operations Research, Columbia University. 12. Ellen A. Cherniavsky '73: Brookhaven National Laboratories, Upton, Long Island, New York. 13. Ajit K. Tamhane '75: Department of Industrial Engineering and Management Sciences, Northwestern University. 14. Donald Gross '62: Department of Operations Research, The George Washington University. 15. Fernando Garagorry '71: EMBRAPA, Brasilia, Brazil.*

*16. David N. Freeman '36: Ketron, Inc., Wayne, Pennsylvania. 17.* Lee W. Schruben: simulation. *18. William G. Costello '73: Sidney Farber Cancer Center, Boston, Massachusetts. 19.* Robert W. Deming (visitor): Department of Mathematics, State University of New York at Oswego. *20. James R. Fergusson '74: Bureau of Management Consulting, Supply and Services, Ottawa, Canada.*

*21. Brant E. Fries '72: Center for Community Health Systems, Columbia University. 22.* Bruce Turnbull '71: applied statistics. *23. Mainak Mazumdar '66: Westinghouse Electric Corporation, Pittsburgh, Pennsylvania, 24. Henry M. Goldberg '76: Faculty of Business Administration and Commerce, University of Alberta, Canada, 25. Jeffrey J. Green '72: School of Business, Ball State University.*

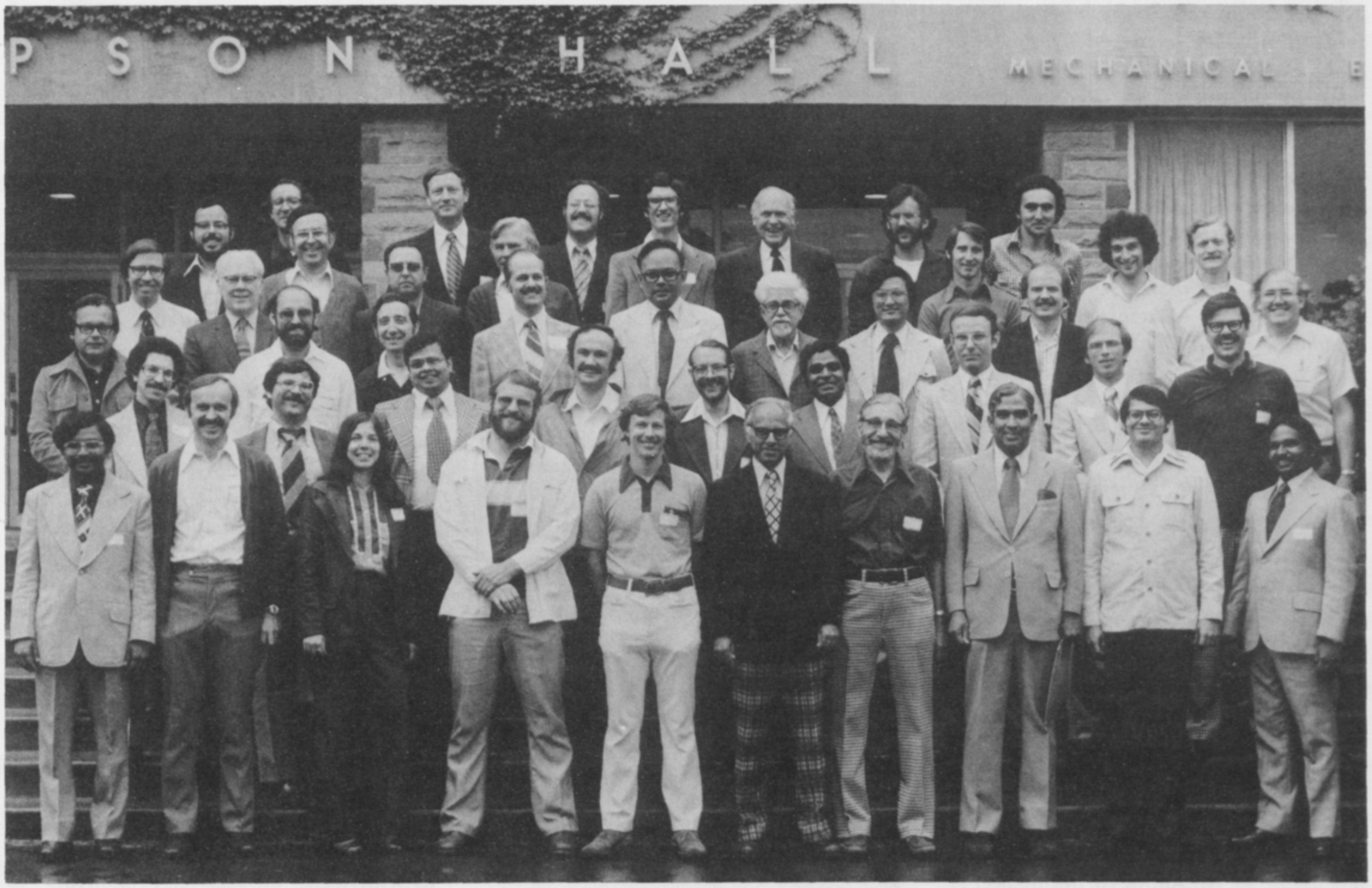
*26.* Lionel I. Weiss: statistical decision theory. *27.* Henry P. Goode (emeritus): industrial statistics. *28.* Andrew Schultz, Jr.: systems analysis. *29. Udai K. Garg '77: Jodhpur (Rajstahan), India. 30.* Robert E. Bechhofer: applied statistics.

*31. Francis Hsuan '74: Department of Statistics, Temple University. 32. Stephen R. Kennedy '73: Department of Industrial and Systems Engineering, San José State College. 33. Wayne F. Bialas '75: Department of Industrial Engineering, State University of New York at Buffalo. 34.* Leslie E. Trotter, Jr. '73: discrete optimization. *35.* Narahari U. Prabhu: stochastic processes, queuing.

*36. Douglas R. Miller '71: Department of Mathematics, University of Missouri. 37.* Louis J. Billera: game theory, combinatorics. *38. Deepak K. Merchant '74: Stanford Research Institute, Menlo Park, California. (We report with regret that Dr. Merchant was recently killed in an accident in Squaw Valley.) 39. John S. Ramberg '69: Program in Industrial and Management Engineering, The University of Iowa. 40.* Murad S. Taqqu: applied probability and statistics.

*41.* John A. Muckstadt: inventory and logistics control. *42. Robert E. Bixby '72: Department of Industrial Engineering and Management Sciences, Northwestern University. 43. Kripa Shanker '77: Department of Industrial and Management Engineering, Indian Institute of Technology, Kanpur, India. 44.* David C. Heath: applied probability.

*Cornell professors not in the picture, and their specialty areas, are* Richard W. Conway '58: information processing systems; William F. Lucas: game theory, combinatorics; George L. Nemhauser: mathematical programming; Thomas J. Santner: applied statistics; Howard M. Taylor 3d: applied probability; *and* Michael J. Todd: mathematical programming.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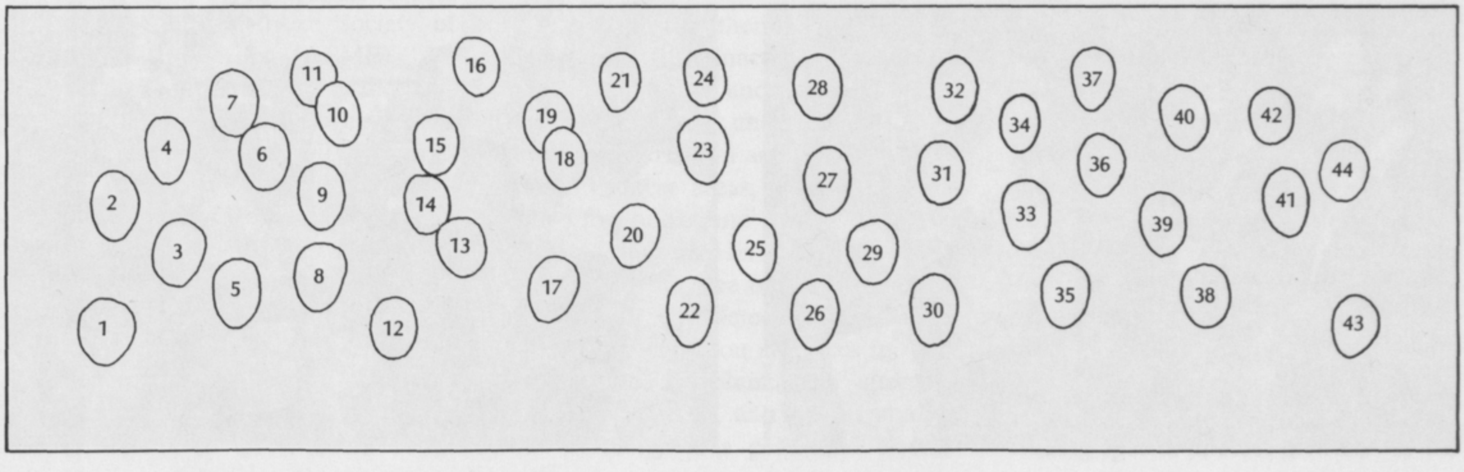
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*The operations research reunion and conference program, arranged by Professor N. U. Prabhu, included an opening picnic, talks by sixteen of the alumni, and a banquet.*

*1. Informal discussions often followed the presentation of papers. This group of professors and alumni, all with a special interest in statistical problems, are (left to right) Bob Bechhofer, Ajit Tamhane, John Ramberg, Wayne Bialas, Uma Prabhu, and Tom Santner.*

*2. "Awards" were presented at the banquet by faculty member Bruce Turnbull. Here Jim Ferguson receives a ruler as a prize for writing the longest Ph.D. dissertation.*

*Presiding at the banquet was Robert E. Bechhofer, then director of the School of Operations Research and Industrial Engineering. Speakers were Andrew Shultz, Jr., who served as head of the department that preceded the School, and later as dean of the College of Engineering; Byron W. Saunders, former director of the School and (at the time of the reunion) dean of the University faculty; and Edmund T. Cranch, who was then dean of the College.*

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*3. A variety of activities is represented by alumni delegates (left to right) Bob Rovinsky, mathematical analyst; Steve Kennedy, college professor; Bill Costello, coordinator of multiclinic cancer trials; and Ellen Cherniavsky, energy analyst.*

*4. Reminiscing in the Upson Hall lobby are (left to right) alumni Mark Eisner, Dave Freeman, Warren Walker, and Ed Ignall. Walker and Ignall are recent award winners; they shared in the 1976 Systems Science Prize Competition of NATO and Walker also received the 1975 Lanchester Prize of the Operations Research Society of America.*

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# REGISTER

■ After completing thirty years on the Cornell faculty this summer, Dennis G. Shepherd became the John Edson Sweet Professor of Engineering, emeritus. During his years in the College of Engineering, he served as head of the Department of Thermal Engineering and as director of the Sibley School of Mechanical Engineering, now the Sibley School of Mechanical and Aerospace Engineering.

Shepherd has been recognized nationally and internationally, as well as at Cornell. His honors include the 1976 Worcester Reed Warner Medal awarded by the American Society of Mechanical Engineers (ASME) "for noteworthy contributions to the permanent literature of engineering." Also, he has been a Guggenheim fellow and a senior visiting fellow of the Organization for European Economic Cooperation (in both cases at Imperial College, London). At Cornell he was selected in 1968 and in 1975 for the annual Tau Beta Pi–Cornell Society of Engineers Excellence in Engineering Teaching Award, the only professor to have been named twice.

A specialist in thermal power, fluid dynamics, turbomachinery, aerodynamic propulsion, and energy sources, Shepherd offered undergraduate and graduate instruction and supervised research in these areas, and he has published five books and numerous papers on these subjects. His most recent work has been in the area of energy sources; he recently completed a comprehensive review paper on advances in wind power for a volume on alternate sources of energy, and he has studied the feasibility of a peak-load electric power system utilizing liquid air for energy storage and the design of power plants utilizing geothermal energy.

Shepherd, a native of England, studied at the University of Michigan for B.S. degrees in engineering physics and in engineering mathematics, both granted in 1934. Before joining the Cornell faculty in 1948, he participated in the pioneering research and development work on turbojet engines and gas turbines in England and Canada. During his years at Cornell, he has served as consultant to a number of industrial firms.

At Cornell he has served on a number of important committees. For the College of Engineering, he was chairman of the policy committee, of a study group on the core curriculum, and of a committee on evaluation of teaching. At the University level he was a member of committees on the academic calendar, on student development support services, on University education, and on geology.

Throughout his career, he has been active in professional organizations, including special-interest divisions of the

Spencer

Shuler

Liu

ASME. He is a member of the Combustion Institute, the Institution of Mechanical Engineers (United Kingdom), and several professional honorary societies.

Shepherd and his wife, Gertrude, plan to remain in Ithaca.

■ Lawrence B. Spencer retired in January after more than forty-one years at Cornell as a staff and faculty member in electrical engineering. He was born in Ithaca, educated in the local public schools and at Cornell, and is maintaining his home here with his wife, Jean.

Spencer received the Cornell degree of Electrical Engineer in 1934 and began his long career at the University in 1936. His specialty field is electrical machinery, and for many years he supervised the laboratory instruction in that area.

His first position at the University was as a research assistant in the construction, design, and testing of electrical apparatus and materials in connection with research projects. Subsequently he served as a mechanician in the electrical laboratory and then, from 1942 to 1954, as an instructor in laboratory courses. In 1954 he began working with Professor Simpson Linke on the installation of an A-C Network Calculator at Cornell and was in charge of the operation of this equipment, which was used for power studies by numerous public utilities and consulting firms. Beginning in 1961, he taught full-time as a senior lecturer in electrical engineering. Among his responsibilities was supervision of the Electrical Engineering Standards and Calibration Laboratory. He was active also as a faculty adviser for undergraduates.

Spencer's professional experience included summer work and consulting for a number of companies, including Corning Glass Works, Detroit Edison Company, Bendix Aviation Company, and the New York State Electric and Gas Corporation.

He is a member of the Institute of Electrical & Electronics Engineers and a charter member of the Power Engineering Society.

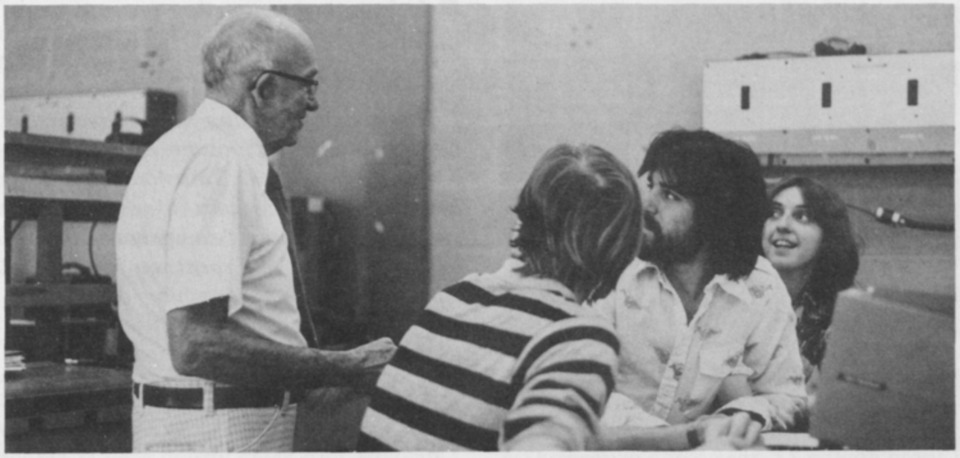
■ This year's Award for Excellence in Engineering Teaching went to *Michael L. Shuler,* assistant professor of chemical engineering. The award, which is accompanied by a $1,000 prize, is sponsored by the Cornell Society of Engineers, an alumni group, and Tau Beta Pi, student honorary society in engineering. The recipient is chosen on the basis of student nominations. Shuler, a specialist in biochemical engineering, holds a joint appointment at Cornell with the School of Chemical Engineering and the Institute of Food Science at Geneva, New York. He came to the University in 1974 after receiving his Ph.D. at the University of Minnesota at Minneapolis.

■ Philip L. -F. Liu of the Department of Environmental Engineering has been granted the first Justice Foundation faculty fellowship in engineering at Cornell. The new fellowship is awarded for outstanding service as an assistant professor. Liu, a specialist in fluid mechanics, hydraulics, coastal engineering, and oceanography, has been a member of the faculty here since 1974.

■ Edmund T. Cranch, who left the Cornell engineering deanship this summer to become president of Worcester Polytechnic Institute, was honored by the Engineering College Council at its spring dinner meeting.

*Left: Charles W. Lake, Jr., former chairman of the Council and currently a University trustee, presents to Cranch the College's Engineering Medal for distinctive service to the College.*

*Right: Arthur Bueche, chairman of the Council, presents gift portraits to the dean's wife, Virginia Cranch.*



*Left: Tom McCarthy and friends.*

■ "The E.E. students' best friend," retiring after twenty-six years at the School of Electrical Engineering, was honored this spring at a student-organized party attended by more than 150 people.

For the past fifteen years, Thomas V. McCarthy, senior electronics technician, has been in charge of equipment for a required junior-year laboratory course commonly referred to as "Super lab" or "Tom's lab." According to Joseph Rosson, associate director of the School, "Tom has a wonderful rapport with our students. He knows every one of them. He knows where they are from and who their friends are. He will call students at their Ithaca residences to awaken them so that they will not be late for classes, and he watches after them to make certain they turn in their work on time."

"The E.E. students' best friend" was part of the inscription on a plaque presented to McCarthy at the party by Eta Kappa Nu, student honorary society in electrical engineering. Other gifts included a $400 travel voucher.

■ Twenty-one new members, a slate of new officers, and a new faculty adviser were welcomed at the spring induction ceremony of Chi Epsilon, student honorary society in civil engineering. Senior Eric Cyker became president and Anthony R. Ingraffea became adviser. The society's activities include conducting a course evaluation survey and operating the coffee shop in Hollister Hall.


*Right: Ingraffea (at left) is presented the Chi Epsilon Professor of the Year Award by Rafael Riera, 1977–78 vice president.*

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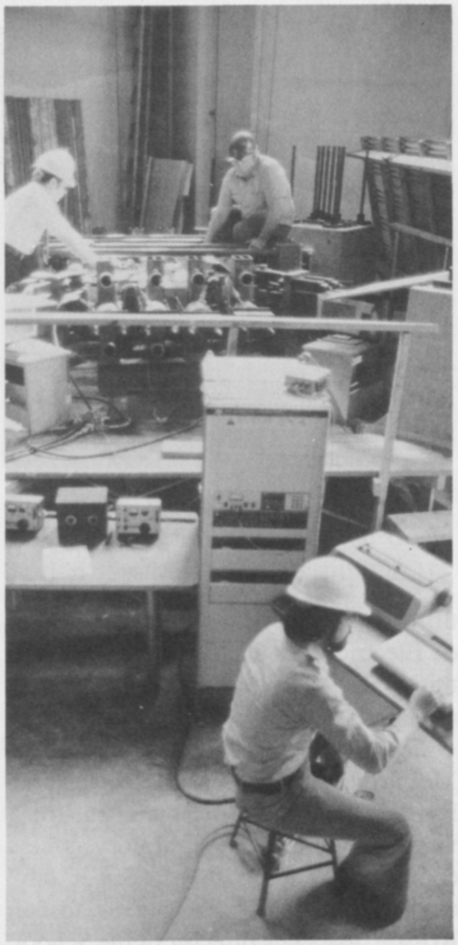

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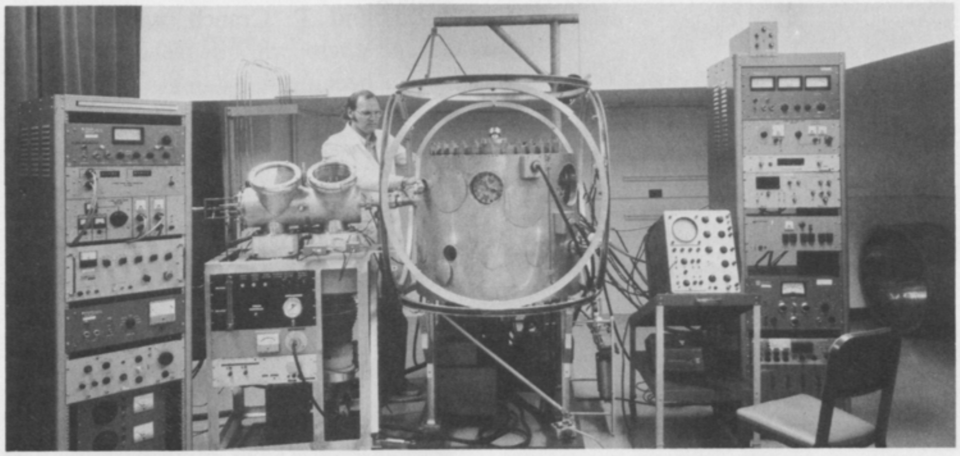

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■ Laboratory renovation projects were in full swing in buildings all around the engineering campus this spring.

*1. The structural testing capability of the George Winter Laboratory, located in a 45-foot-high bay in Thurston Hall, was being upgraded as part of the University's $230 million campaign. Almost $200,000 has been spent so far in the laboratory project; a major contributor has been the Bethlehem Steel Corporation. Here a model of a concrete containment vessel for a nuclear reactor is tested for behavior under stresses such as earthquakes.*

*2. This "semiclean" laboratory has been established in Olin Hall for research directed by Robert P. Merrill of the School of Chemical Engineering. Merrill's work includes studies of solid-surface structure and of gas–solid collision dynamics.*

*3. The new Olin Hall laboratory is situated in what used to be a virtually unused basement storage area. Because it is built on bedrock, the facility provides stability for vibration-sensitive experiments.*

*4. A minicomputer laboratory is another new research installation in Olin Hall. The renovation and equipment was financed by a grant from NSF with match-*

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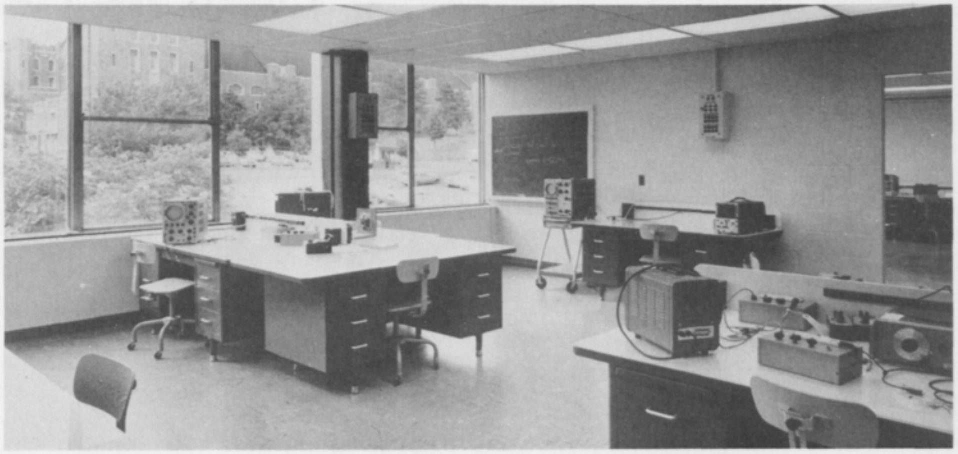

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*ing funds from the Glenmede Trust Company. (The half-million-dollar Glenmede grant was awarded to the College for the establishment and modernization of teaching laboratories.) Shown are Professor Keith Gubbins, who is conducting simulation studies of liquids, and his postdoctoral associates Paulette Clancy and Steve Thompson.*

*5 and 6. The refurbishing and equipping of a laboratory for electrical engineering project work was financed through a $60,000 grant from the Emerson Electric Company. The laboratory, a suite of four rooms, is used mostly by M.Eng. students.*

*7. A vertical wind tunnel two stories high was installed in Grumman Hall for NSF-sponsored research on atmospheric turbulence. The project is headed by John L. Lumley of the mechanical and aerospace engineering faculty. Shown are Professor Zellman Warhaft and (below) Edward Jordan, research support specialist.*

*8. An ion implanter is being installed in the new National Research and Resource Facility for Submicron Structures in Phillips Hall. Shown are graduate student Gary Harris (left) and research machinist Nelson Allen. The facility is funded by NSF through a five-year, $5 million grant.*

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■ Scholarships, a professorship, and a departmental development program are among the benefits of recent gifts from foundations and individuals.

*1. Geology field trips are among the activities of the Department of Geological Sciences to receive support from a recent bequest that will probably exceed $5 million in value. The gift, from an anonymous donor, is one of the largest ever given to a single department at Cornell. According to Jack E. Oliver, chairman, the money will help develop a department that is "unexcelled in the history of the earth sciences." The photograph was taken last summer during a five-day raft trip down the Green River, part of a western United States field course.*

*2. A new specimen is deposited in the "rock park" that is the result of another gift to the Department of Geological Sciences. Meyer Bender '29 supplied funds for the collection, which is situated on either side of the entrance to the department's quarters in Kimball Hall. The newest section of the park features specimens gathered from quarries, construction sites, and other locations in New York State.*

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*3. A Master of Engineering (Chemical) scholarship holder this past year was Jan Slaby (left), shown with his faculty adviser, Michael L. Shuler. Recently established scholarships honor two former directors of the School, Charles C. Winding and the late Fred H. Rhodes.*

*4. Observing the appointment of the first Willis H. Carrier Professor of Engineering are, left to right, engineering Dean Edmund T. Cranch; Cornell President Frank H. T. Rhodes; John L. Lumley, the chairholder; and George D. Hudelson and Richard Morris, representatives of the Carrier Corporation.*

# FACULTY PUBLICATIONS

*The following publications and conference papers by faculty and staff members and graduate students of the Cornell College of Engineering were published or presented during the period November 1977 through February 1978. Earlier publications inadvertently omitted from previous listings are included here in parentheses. The names of Cornell personnel are in italics.*

## ■ AGRICULTURAL ENGINEERING

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*Ludington, D. C.*, and *Sobel, A. T.* 1977. Storability of partially dried laying hen manure. In *Food, fertilizer and agricultural residues*, ed. *R. C. Loehr*, pp. 581–598. Ann Arbor, Michigan: Ann Arbor Science Publishers.

*Martin, J. H., Jr.*, and *Loehr, R. C.* 1977. Economic comparison of the oxidation ditch and high-rise manure drying as poultry waste management alternatives. In *Food, fertilizer and agricultural residues*, ed. *R. C. Loehr*, pp. 533–548. Ann Arbor, Michigan: Ann Arbor Science Publishers.

*Masemore, B. J.*, and *Rehkugler, G. E.* 1977. Influence of Tractor Geometry and Mass on Side Overturns. Paper read at Winter Meeting of American Society of Agricultural Engineers, 13–16 December 1977, in Chicago, Illinois.

*McCarty, T. R.*, and *Ludington, D. C.* (1977). The Effect of Wood Shavings on the Conservation of Nitrogen in an Aerated, Solid Manure Treatment System. Paper read at North Atlantic Regional Meeting of American Society of Agricultural Engineers, 31 July–3 August 1977, at University of New Brunswick, Fredericton, Canada.

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*Rand, R. H.*, and *Cooke, J. R.* 1977. Fluid Dynamics of Phloem Flow: an Axisymmetric Model. Paper read at Winter Meeting of American Society of Agricultural Engineers, 13–16 December 1977, in Chicago, Illinois.

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*Davis, H. A.; Rej, D. J.;* and *Fleischmann, H. H.* 1977. Production of Field-Reversing Electron Rings by Ring Stacking. Paper read at 19th Annual Meeting of Plasma Physics Division, American Physical Society, 7–11 November 1977, in Atlanta, Georgia.

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*Liboff, R. L.* (1977). Conjectured superfluidity of deuterium. *Physics Letters* 61A:244–246.

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*Rej, D. J.; Davis, H. A.;* and *Fleischmann, H. H.* 1977. Translation of Relativistic Electron Rings into Low Density Background Gas. Paper read at 19th Annual Meeting of Plasma Physics Division, American Physical Society, 7–11 November 1977, in Atlanta, Georgia.

*Salpeter, M. M.; McHenry, F. A.;* and *Salpeter, E. E.* 1978. Resolution in electron microscope autoradiography. IV. Application to analysis of autoradiographs. *Journal of Cell Biology* 76:127–145.

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*Smith, A. C.; Swannack, C. E.; Fleischmann, H. H.;* Schrandt, R. G.; and Thompson, W. L. 1977. Energy measurements on fast-pulsed near-relativistic electron beams using bremsstrahlung absorption spectroscopy. *Review of Scientific Instruments* 48(12):1610–1616.

*Tuszewski, M.*, and *Fleischmann, H. H.* 1977. Magnetic Compression of Strong Electron Rings. Paper read at 19th Annual Meeting of Plasma Physics Division, American Physical Society, 7–11 November 1977, in Atlanta, Georgia.

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Leng, C. A.; Rowlinson, J. S.; and *Thompson, S. M.* 1978. The gas–liquid surface of the penetrable sphere model II. *Proceedings of the Royal Society of London A* 358:267–280.

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*Brutsaert, W.* 1977. The concise formulation of diffusive sorption of water in a dry soil. (Reply.) *Water Resources Research* 13(6): 1021–1022.

*Chowdhury, A. H.*, and *White, R. N.* 1977. Materials and modeling techniques for reinforced concrete frames. *Journal of the American Concrete Institute* 74:546–551.

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