II. DETERMINING NEED: VARIATIONS BETWEEN FIELDS

Virtually no field of research is untouched by the potential of new instrumentation or computing devices to accelerate the acquisition and analysis of data. The knowledge available to the undergraduate in science or engineering may have been derived recently from research employing state-of-the-art equipment. [t is essential, therefore, for the undergraduate to be able to understand the fundamental principles underlying the instrumentation. While developments in research technology have affected all fields in science and engineering, the fields mentioned most frequently in terms of advances in instrumentation were chemistry and engineering. Biology, physics, and the social and behavioral sciences were also mentioned, though less frequently than chemistry and engineering. Each field is discussed in this section.

Engineering

From the educators' and often from the engineering profession's point of view, engineering education has been affected by an unfortunate timing of factors — enrollment trends, advances in technology, and cuts in state financial support — which has often placed needed equipment beyond the range of the typical college budget. Enrollments at engineering schools have more than doubled since 1973.[5] Thus, the quantity of laboratory equipment needed has increased as well. According to the National Society of Professional Engineers (NSPE), engineering schools have not kept pace with the necessary increase in the amount of equipment.[6] Between 1971 and 1982, B.S. engineering degrees awarded increased by 60 percent. By contrast, the number of

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5. W. Edward Lear, American Society for Engineering Education, Washington, DC, interview, 1985.
6. National Society of Professional Engineers, Engineering Education Problems: The Laboratory Equipment Factor (Alexandria, VA: September 1982), p.3.

Laboratory “student stations” increased by onIy 9 percent.

Increased enrollments have stressed the equipment budgets of colleges and universities. But such stresses are not new. In the 1960s, enrollment in engineering schools rose dramatically. What is different today is an ongoing revolution in the design and development of equipment and fewer programs of financial assistance. This revolution, which has been brought about by the ever increasing capabilities of microprocessors, has made it even more difficult for schools to meet the demands for more, newer, and better equipment. Designers of this equipment believe that important discoveries are being made in the fields of computer science and electronics every 18 months. Not only have these advances placed additional stresses on equipment budgets, but they have also increased the course requirements for students in many subdisciplines of engineering, including electrical engineering, mechanical engineering, computer engineering, materials science engineering, and chemical engineering.

While enrollments and the rate of technological innovation have increased, state support for engineering schools has decreased. Since 60 to 70 percent of engineering schools are supported by state appropriations,[7] state support is a major issue. The decline in state sources of financial support began in the early 1970s. In the last 2 to 5 years, however, several state legislatures have increased funding for engineering equipment support, often because of concern that industries will be attracted to other states with more up-to-date graduates.

There is evidence to suggest that this concern is well founded. According to the NSPE study cited above, some professional engineers contend that schools are not keeping up with modern technology:

> Continuing obsolescence of laboratory equipment and instruments has placed many schools in the position of not being representative of modern professional practice . . . Rapid evolution of

7. Lear, op. cit.

> such fields as robotics, microelectronics, computer-aided design, optics, spectrographic, electron microscopy, computer-graphics, etc., has left the universities in a teaching mode far behind current professional practice. Students are not being adequately prepared to work with confidence in many areas of engineering.

W. Edward Lear, Executive Director of the American Society for Engineering Education, has suggested one reason why engineering schools are unabIe to keep pace with technological deveIopments: universities historically have spent a smaller proportion of funds to update equipment than industry. Lear estimates that schools spend 3 to 5 percent of the book value of their equipment on new purchases annualIy while industry spends 10 percent of the book value of its equipment.

It is important to note that there is no agreement about the actual extent of obsolete equipment, nor is there agreement about the cost of modernization. Various studies have used different methodologies to derive appropriate cost figures. For example, the NSPE study attempts to quantify the magnitude of the equipment problem through a survey of 26 engineering schools representative of different size enrollments and of public and private institutions. It concludes that if schools were to restore their laboratories in 1981 to the relatively up-to-date status they achieved in 1971, $1.2 billion would be required for the 250 accredited engineering schools. If, in addition, increased equipment needs caused by student enrollment growth are accounted for, the total equipment shortfall would be on the order of $2 billion. The survey found that equipment needs are ‘remarkably consistent between the various groups˜representing public, private, small, and large schools. They also found that an annual expenditure on laboratory equipment of $400 per student — or of $2,000 per B.S. degree awarded — could have prevented this decline in the quality of laboratory equipment.

As a result of this decline, engineering universities are facing difficulties in receiving desired levels of accreditation. ‘Recent comments by the Accreditation Board for Engineering and Technology officials tend to indicate that nearly half of

8. National Society of Professional Engineers, op. cit., p. 32.

accreditation actions in recent years are for less than the maximum 6-year cycle . . . and the primary factor is the deteriorating condition of the engineering laboratories," according to the NSPE report.[9] A 1984 report issued by the American Electronics Association (AEA) reports that the Accreditation Board found that 87 of the Nation's 240 engineering programs had 'unsatisfactory' instructional labs in 1982. Only 8 of the 240 received an 'excellent' or 'outstanding' rating.[10]

In a 1984 AEA survey of electrical engineering department heads, 39 percent of the respondents indicated that they currently have instructional equipment that is not usable. Thirty-one percent said they turned down offers of equipment donations because they lack service and repair monies. Respondents indicated they needed, on average, an additional $21,000 over the budgeted amount for equipment at their department (AEA Status Report).[11]

Interviews with Engineering Deans

In interviews with OTA, educators representing both State and private schools agreed on several major points:

- The field of engineering is undergoing an equipment revolution primarily because of computers.
- Schools are having an extremely difficult time finding financial resources to pay for new equipment.
- The cost of equipment is widening the gap in the quality of education offered by a handful of prestigious schools and the remaining engineering schools.

The MIT's and the Stanfords can eventually afford to buy all this. The majority of

9. National Society of Professional Engineers, op. cit., p. 4.
10. Pat Hill Hubbard and Kay Storm, AEA Status Report on Engineering and Technical Education (Palo Alto, CA: American Electronics Association, 1984), p. 19.
11. op. cit., p. 20.

engineers aren't educated there. We need a wide-scale diffusion [of equipment]," said Fred Landis, Professor of Mechanical Engineering and former dean at the College of Engineering, University of Wisconsin at Milwaukee.

MIT's Chairman of the Electrical Engineering Department, Joel Moses, confirms this view. "We are doing a pretty good job because of corporate gifts . . . . If we didn't have corporate gifts, it would be a disaster." Moses credits a $50 million gift to MIT from IBM and DEC of high-performance personal computers which became the cornerstone for 'Project Athena." He noted that at the time of the gift, the companies hadan interest in promoting and testing their computers before future engineers.

Karl Willenbrock, professor of electrical engineering at Southern Methodist University (SMU), says the financial problems are intensified for a small, private schools likeSMU. 'There is no relation between the costs of modern instruments like CAD-CAM and computer graphics and the budget of a small university for equipment, typically $50,000 per year . . . . This trend distorts engineering education. Schools now teach theoretical courses because they don't have the equipment to teach lab courses.~

Engineering faculty mentioned the following equipment most frequently as that which is needed most, but is least affordable:

- Conversion of laboratory equipment from analog to digital;
- computer-aided design (CAD) costing from about $150,000 to several million dollars;
- robotics equipment ($10,000 to $50,000 for a simple arm);
- powerful personal computers;
- oscilloscopes; and
- chemical processing equipment.

CHEMISTRY

Chemistry was mentioned frequently by both faculty and industry as one of the disciplines with the most rapid advances in instrumentation. An American Chemical Society (ACS) report reflects the concern within the profession that the increasing cost of chemistry equipment is leading to reduced laboratory training for chemists, and ultimately to a poor education:

> There is widespread concern that both the quantity and quality of laboratory experience in baccalaureate degree programs is decreasing. The requirements for formal laboratory work have always been less in the United States than in other industrialized nations, but increasing costs of modernization, upgrading or even sustenance of present levels of quality generate pressures which are resulting in even less favorabIe comparisons than before. Many students awarded bachelor's degrees in chemistry have very limited experience with modern laboratory techniques and even less experience in the design, formulation, conduct and analysis of experiments . . . . As the content of the chemistry curriculum has become more theoretical, more student time is spent in the classroom and in the pursuit of solutions to formal problems and less in the laboratory learning and perfecting those techniques which establish and maintain the real contact of a chemist with the material world. Students develop little feeling for the behavior of matter— which, ultimately, is what chemistry is all about.

The report goes on to criticize computer simulation of experiments as another force driving students further away from the actual laboratory experience that would help them to comprehend natural phenomena. The report states that the escalation in the cost of laboratory equipment that has occurred during the past 10 to 15 years 'threatens to wipe out earlier gains˜made by educators who brought more sophisticated instruments into the student laboratory.

ACS attempted to quantify the instrumentation problem in their report:

1) The mean age of all chemistry instruments at small, primarily undergraduate schools, is 8.9 years. The seven most commonly used instruments are over 10 years old. The report notes that, by today's

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12. American Chemical Society, Tomorrow — The Report of the Task Force for the Study of Chemistry Education in the United States (Washington, DC: October 1984), p.42.

standards, such equipment is “too old. ” A widely held estimate for the optimum useful life of a typical research instrument is about 7 or 8 years. After that, instruments need to be repaired more often or replaced because they have become obsolete. For example, over the last decade, microprocessors have been incorporated into spectrometers and chromatography, the “cornerstones of chemical instrumentation, ” to a high degree. It is now possible with Fourier transform data reduction methods to obtain spectra of very weak signals and to reduce the time required to make measurements from several hours to a few minutes. In some cases, the evolution of existing technologies has rendered existing equipment outdated. An example is mass spectrometry, where “new sample handling systems have been developed to extend the range of compounds that can be studied and new ion source have made it possible to study larger molecules than ever before. ”

2) The cost of equipping all 470 ACS-accredited small schools (primarily undergraduate) with needed equipment is estimated at $65.6 million. This figure is extrapolated from the cost estimates for instrumentation needs of 66 chemistry depart merits at small schools, which came to a total of $9.2 million.

3) Instrument maintenance budgets reported by responding departments were low in comparison to what are believed to be adequate budgets. Trained maintenance technicians are “all but nonexistent” at small departments, severe problem,” says the report, in view of the age of equipment.[15]

ACS received responses from 32 “major” and 71 “smaller” chemistry departments.[16] A major department is one in an institution in the top 100 in total R&D expenditures in chemistry, according to the National Science Foundation (NSF). “Smaller” departments are defined as those not in the top 100. While the latter category includes some departments with Ph.D. programs, these schools generally emphasized instruction more than the major departments. Smaller chemistry departments, according to the ACS report, plan to devote 69 percent of newly acquired equipment to the combined purposes of undergraduate instruction and research training, 22 percent to research training only, and 9 percent to undergraduate instruction only.

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13. American Chemical Society, Joint Task Force of the Committee on Science, and Committee on Chemistry and Public Affairs, Instrumentation Needs of Academic Departments of Chemistry, A Survey Study (Washington, DC: April 1984), p. 11-13.
14. Ibid., p. 18.
15. Ibid., p. 11.
16. Ibid., p. 2.

When ACS asked the schools to list their needs in research and instructional equipment, seven instruments were mentioned most frequently. Schools were asked to exclude computers and equipment that would cost less than $5,000 at today's prices from their list of equipment needs. The instruments listed below are consistent with the needs identified in OTA's interviews of undergraduate faculty. The list is identical, with the exception of number 7, with the equipment requested most frequently in chemistry grant proposals to NSF's College Science Instrumentation Program.[17]

1. Ultraviolet-Visible Spectrophotometer
2. Gas Chromatography
3. Nuclear Magnetic Resonance Spectrometer (NMR)
4. Infrared Spectrophotometer
5. Mass Spectrometer
6. Liquid Chromatograph
7. Atomic Absorption Spectrophotometer

In OTA interviews, chemistry department faculty mentioned NMR's most frequently as the instrument they need the most, but can afford the least. The cost of this instrument for undergraduate use ranges from $40,000, for the 'least expensive one" according to a small, private college representative,[18] to $200,000 for an NMR that could also be used for research.[19] Yet faculty members believe this cost can be justified because the use of NMR has changed the substance of knowledge in chemistry.

These faculty remember when NMR was a research instrument only one generation ago, when they were graduate students. Then, the instrument was less reliable, more difficult and more time-consuming to use than today's NMR. Now, 'it can deal with

17. <u>Chemical and Engineering News</u>, "NSF Sums Up First Year of Instrumentation Program/f vol. 63, Sept. 30, 1985, p. 25.
18. Julia Jacobsen, Association of Affiliated College and University offices, Washington, DC, interview, 1985.
19. Marshall Cronyn, Reed College, Portland, OR, interview, 1985.

nuclei that precursor instruments could not have touched," says Violet Meek, a chemist who now represents a group of about 300 small, private colleges in the Council of Independent Colleges. Science students beyond first-year chemistry are expected to be familiar with NMR's, Meek says.

Since most undergraduate chemistry departments can afford only one NMR, at best, hands-on experience is necessarily limited. Schools described a variety of ways in which the instrument would be used. In some cases, students would observe, rather than manipulate, the instrument to learn its purpose. In other cases, students would use the NMR in the junior or senior year while working with faculty on research projects.

Simulation of instruments (not experiments) through the use of personal computers may partially resolve the problem of the lack of hands-on experience. At the University of Wisconsin, Madison, for example, chemists are effectively simulating the operation of NMR machines on personal computers. This simulation uses a library of spectra of actual materials. The software is used to train students, prior to use of the actual machines, in order to make the process more efficient and the equipment more available.[20]

Because of the improved speed and reliability of the new generation of equipment, such as gas chromatography and NMR's, faculty contend students are now able to spend more time concentrating on the purpose of the equipment and less on the drudgery of collecting data or fine-tuning the instruments. As a result, science faculty say, undergraduates today are absorbing material that would have been limited to graduate students a generation ago.

Computerized Equipment

The computerization of laboratory equipment has advanced the chemistry

20. Robert L. Clodius, President, National Association of State Universities and Land-GrantColleges, personal communication, 1985.

curriculum. For example, Meek believes chemistry students should have experience with a digital read-out version of a gas chromatography instead of with the strip chart recorder of the previous generation's gas chromatography. She contends that the student who works in industry who has had experience with digital-generation equipment will realize that data can be obtained more quickly. This affects how a professional scientist will set up an experiment and what data he or she can realistically expect to find.

Computers are frequently used as a hardware interface to join together two instruments to form a single integrated unit. According to the American Chemical Society, interfacing a gas chromatography to a mass spectrometer is now a widespread practice.[21] This permits the identification of compounds present in such extremely low quantities that they were previously impossible to analyze.

The interface of computers with equipment has affected all disciplines of science. According to Robert Watson, head of NSF'S College Science Instrumentation Program (CSIP), the single most common objective in CSIP grant proposals is the interface with computers of scientific instrumentation, not necessarily the purchase of a computer _se_. Watson notes that such computers are used as an adjunct to instruments already in existence. Usually, Watson says, "there is a scientific instrument to do this, but the computer greatly enhances this ability. "

BIOLOGY

The biological sciences have traditionally required a wide range of laboratory equipment for instructional purposes. Today's basic biology laboratory should be equipped with the following: one light microscope per student (at a cost of $1,000 to $7,000 for a binocular microscope), several balances (as high as 6 to 8 per lab at a cost of

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21. American Chemical Society, Instrumentation Needs of Academic Departments of Chemistry, op. cit.

$2,500 a piece), centrifuges (4 to 5 for one course at $30,000 to $50,000 each), expensive chemicals and glassware, autoclaves, incubation equipment, refrigerators, and all of the brick and mortar requirements not restricted to bench tests such as floor space; head room; water, air and gas lines; power sources; and ventilation. While many colleges and universities already have these facilities and instruments on hand, they are often outdated or in disrepair due to heavy and continual use.

Rita Colwell, Vice President for Academic Affairs and Professor of Microbiology at the University of Maryland, describes the typical situation in an undergraduate microbiology class. There may be as many as 150 students in the introductory course. The instructor must borrow equipment from the graduate department and clean out the entire departmental supply of pH meters for a l-day laboratory session. (Often other research has to stop for a day.) Finally, the equipment may be broken or may need to be recalibrated when it is returned to the research laboratory.

According to Colwell, the cost of teaching a student in virology has more than doubled from $1,000 per student in 1976 to $2,500 per student today. She says that between 1972 and 1983, the university's budget for purchasing scientific equipment was extremely tight. "For a period, we couldn't afford to buy supplies such as tissue cultures and petri dishes — and we cut out Iabs. Now, as a result, we are graduating students in microbiology, with only two laboratory courses, to work in hospitals and food laboratories (as technicians). They don't know how to use a centrifuge or a spectrophotometer."

Colwell said a biology student should have the opportunity to do experiments in an introductory course that may require four to five instruments per course at a cost of $30,000 to 50,000 each. She also contends that upper level and honors students should have the opportunity to work on an electron microscope as an apprentice to a researcher. Electron microscopes range in price from $100,000 to $200,000 and were most frequently mentioned as the piece of equipment most needed by biology depart ments. The need is one per department.

“You cannot train students in microscopy without [electron microscopes],” Colwell believes. The University of Maryland, Department of Microbiology, only recently received its new electron microscope through a Defense Department research grant. Now, Colwell says, undergraduates can view microorganisms with the electron microscope in a cytology course but are not permitted to manipulate it because the instrument is too delicate.

Other equipment needs were cited in connection with the fields of biotechnology and recombinant DNA research. Biology has become more molecular and more chemical in its orientation ever since the DNA revolution. One way that the change in the field is filtering down to undergraduates is the increasing introduction of biochemistry courses for undergraduates. Demand for this course has increased both as a result of scientific discoveries and of the burgeoning job market in the biotechnology industry for those with undergraduate degrees only.[22] As a result of the discoveries and the changes in curriculum, the kind of sophisticated instrumentation used in chemistry is now more frequently used in biological research. Colleges stated that NMR’s and spectrophotometers are now being used both by undergraduate biology and chemistry majors.

In some cases, colleges still need to equip an entire lab for biotechnology work. If built from scratch, establishing a biotechnology laboratory that would serve 10 to 15 students can cost $200,000, but colleges often have in their inventory some of the basic instruments that are also common to other biology courses. The following types of equipment are needed to set up an instructional biochemistry laboratory, according to Dale Edmondson, associate professor of biochemistry at Emory University School of Medicine in Atlanta, Georgia, and Chairman of the Education Committee for the American Societ of Biological Chemists:

22. Dale Edmondson, Emory University School of Medicine, Atlanta, GA, interview, 1985.

- an ultra centrifuge
- gel electrophoresis;
- chemicals;
- sophisticated camera to photograph cells;
- mass spectrophotometer;
- pH meters;
- cold cabinets;
- autoclave (usually in a biology lab already); and
- incubation meters (usually on hand already).

PHYSICS

In this field, the list of high-cost equipment mentioned by educators as most needed includes:

- Nuclear Magnetic Resonance Spectrometers;
- computers, both interfaced to laboratory equipment and personal computers for analysis;
- oscilloscopes; and
- in a few cases, lasers, for junior and senior physics majors.

The need for the technological capability to interface microprocessor equipment to laboratory data-collection equipment and the conversion of analog equipment to digital were cited most often. However, there were strong disagreements about the necessity of the equipment conversion. While many physics professors felt pressure to convert the majority of equipment to digital read-out, some insisted that the major principles could be taught with more traditional equipment.

John King, physics professor at MIT, asserted, “We will teach them what they need to know if it (equipment) is maintained well and doesn't get 40 years behind." In his view, "no more than 20 percent" of the laboratory equipment needs to be computerized to give students a grasp of how such equipment is operated. "To do an experiment, observing is important. The computer bypasses it."

Other physics professors said it was important to have a happy medium: teaching students the principles on pre-computer analog equipment, but teaching them to be familiar with computer-supported equipment and the capabilities for acceleration of data analysis as well.

Oberlin physics professor Robert C. Hilborn was emphatic about the benefits of the computer for physics. "It has revolutionized how people think about data," he says. Because of the speed of data collection, Hilborn says, "you can think about doing more sophisticated experiments that would have taken endless time to do before. You can let the student do experiments that were not feasible before."

Aside from cutting edge research equipment, Hilborn says, there have been "no striking technological breakthroughs" in physics that have affected the education of undergraduates as NMR's have affected chemistry. As for future advances, Hilborn believes today's oscilloscopes and electronic instrumentation are at a relatively stable point in their abilities, compared to research equipment. Once purchased, it will be 5 to 10 years before there is a need to buy a new version of a recent oscilloscope or personal computer for undergraduate purposes, Hilborn predicts.

One use of computers could lead to cheaper instrumentation. Reed College, for example, uses an Apple personal computer to simulate the face of an oscilloscope on the screen for student laboratories. This eliminates the need to purchase an oscilloscope for every student, according to Reed College Vice President and Provost Marshall Cronyn. According to Professor Hilborn, computers can also be used in introductory physics courses to make the subject 'more exciting˜ for students who are not physics majors.