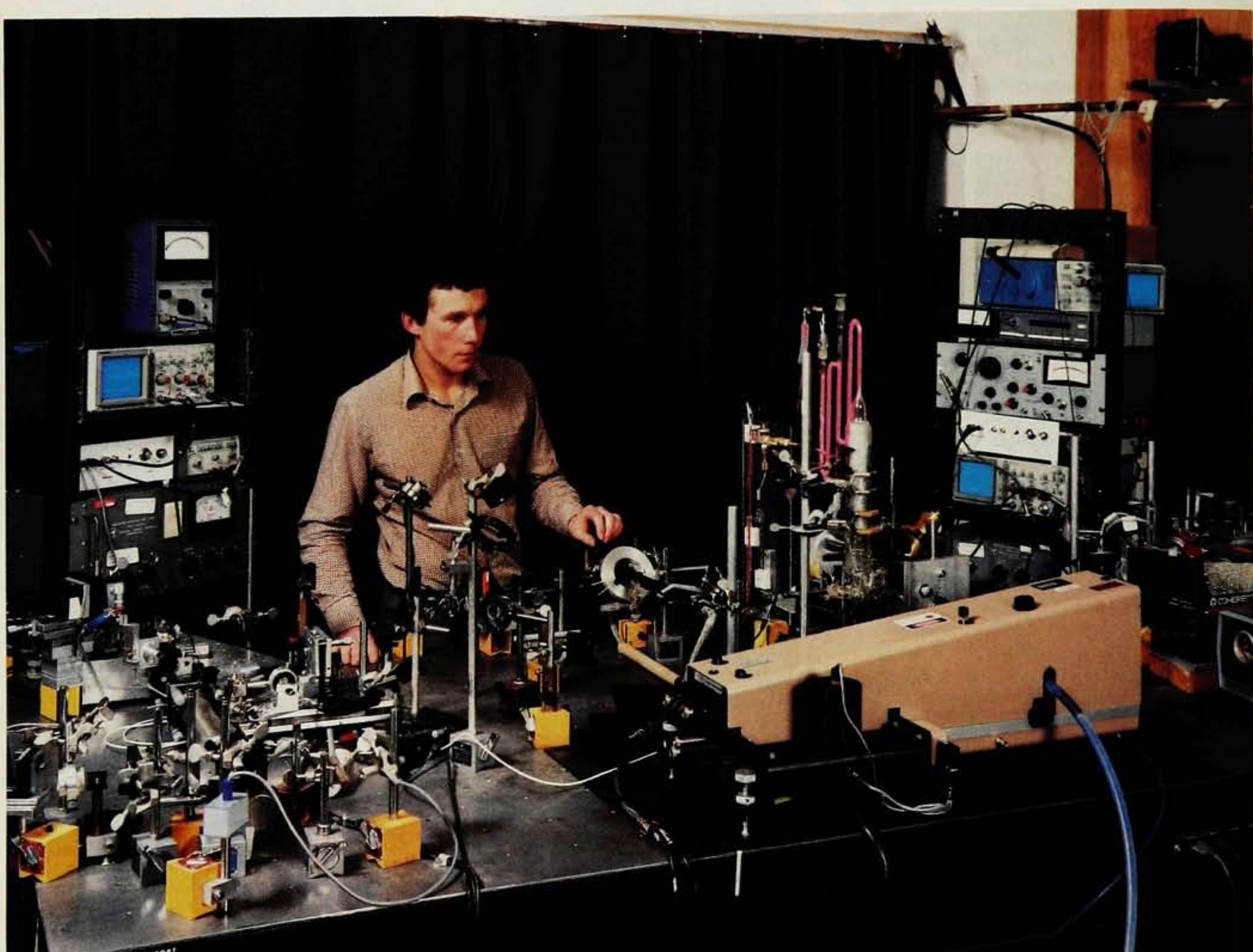

Laser spectroscopy. Frans Alkemade with an apparatus for measuring the two-photon 1s–2s transition in atomic hydrogen by high-resolution Doppler-free spectroscopy in the laboratory of Theodor Hänsch at Stanford. The goal of this experiment is to obtain new values for several fundamental constants, to investigate the limitations of QED in atomic hydrogen and to advance the resolution and accuracy of optical spectroscopy. (Courtesy of Theodor Hänsch.)

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Research in small groups

Small-scale research plays a vital role in advancing physics, in training physicists and in generating new technologies, but we will need a new perspective to judge its needs alongside those for large facilities.

Daniel Kleppner

In Munich's Deutsches Museum one can come upon an Italian Renaissance study, meticulously recreated and handsomely furnished save for one intrusion: A plank, one end propped on a trestle, the other resting on the floor. With such a crude apparatus and using his pulse to clock how long a brass ball takes to roll various distances, Galileo first explored the nature of uniformly accelerated motion. With the aid of these measurements he discovered the basics of dynamics; in so doing he also established a tradition for experimental research that has animated physics ever since.

Galileo created the style of a scientist who devises his own experiment, builds his own apparatus, takes his own data and draws his own conclusions. This is the style of Newton and Cavendish, of Fraunhofer, Faraday and Michelson, of Helmholtz, Roentgen, Rutherford and Millikan.

With the invention of accelerators, plasma machines and other large-scale facilities for research, a different style emerged—"big" physics—in which scientists conduct research in large groups and use facilities that are constructed and operated by others. Such research has generated some of the most exciting advances in physics during the past decades. However, the tradition of physics on a small scale—"small" physics—is also very much alive. Today's small-scale research is generally pursued in small groups rather than by individuals, and even the conceptually simplest experiments are likely to require complex and costly equipment. Nevertheless, this tradition has its share of the triumphs in physics.

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This article attempts to describe the scope of small-scale research in the advance of physics and to show its role in training physicists and generating new technologies. It will discuss the increasing problems that face small research groups—particularly in the universities—and that give cause for concern about the future of this style of research in the United States. It will then propose a fresh perspective that can provide a useful starting point for addressing these problems.

Because of its diffuse nature and varied goals, one could easily overlook physics on the small scale in viewing the enterprise of physics. But, as we shall see, one would overlook much of the best and most valuable of contemporary science, for this research plays a major role in the advances of physics. If the Nobel prize can be used as a guide to what is important and enduring in physics, it is in the areas of small-scale physics that much of the scientific action takes place. Furthermore, these are the areas where physics most frequently interacts with the other sciences and where it has the most direct impact on our national programs and on industry. Thus, viewed collectively, the independent groups assume a clear identity. These groups produce a large fraction of our best science, train over 70 percent of our graduate students and generate much of our new technology.

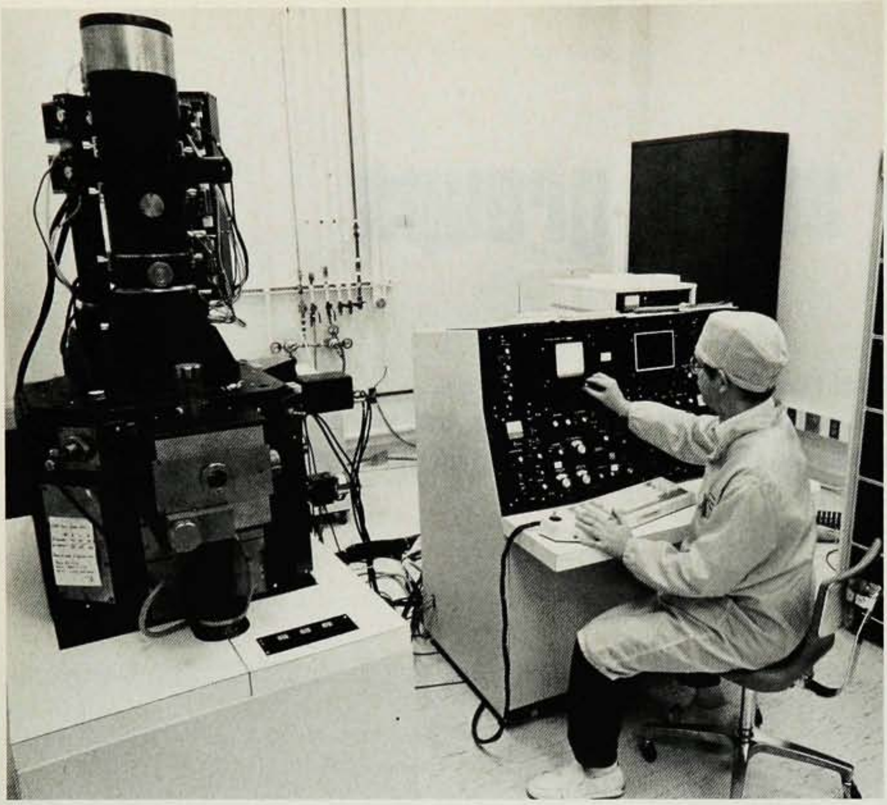
Big and small physics

The distinction between big and small physics stems not from their separate scientific goals but from the experimental style required for effective research. The frontier of particle physics—the archetype of big physics—lies at the highest possible energy that can be attained: Nearly all the experimental research must be carried out by large groups using giant accelerators. The frontiers of condensed-matter physics—the major field of small physics—lie in the study of materials by various types of spectroscopy and other techniques requiring small instruments: Such research is most effectively carried out in small groups. Atomic, molecular and optical physics also thrive in the small-group style, as do portions of nuclear physics, astrophysics and plasma physics. Fluid physics, acoustics and all of the "interface" areas, such as biophysics and medical physics, also belong to small physics.

Small-scale research sometimes requires large user facilities. Synchrotron light sources, for instance, are generally used simultaneously by many small groups. Each group sets its own research goals and supplies its own equipment; usually this research constitutes only one portion of the group's program.

One telling indicator of the difference between small and big physics is the number of authors contributing to a scientific paper. The average number of authors for a *Physical Review Letter* in condensed-matter physics is less than three; in particle physics it is more than 40.

In the United States, small-scale research in physics is organized around approximately 1800 independent groups, some as small as a single faculty member with one graduate student, or an experimenter with a few colleagues in a government or industrial laboratory. Many of these groups are relatively free to shift their goals as



Submicron machining. It has become possible to fabricate devices in the submicron range in which properties of matter are altered qualitatively because of quantum effects. Brian Whitehead is shown here operating a scanning-electron-beam microfabricator in the National Research and Resource Facility for Submicron Structures at Cornell University. The machine is used in the fabrication of superconducting tunneling junctions having an area of 10^{-10} cm^2. Robert A. Buhrman and his colleagues have used such junctions to measure nonequilibrium electron effects in one-dimensional geometries and to study macroscopic quantum tunneling. (Courtesy of Robert A. Buhrman.)

scientific opportunities unfold, and are flexible enough to move rapidly in new directions. Independence is the hallmark of this flexibility, and the research could reasonably be described as "independent group research."

Progress in small physics

A comprehensive description of small-scale research would require summarizing a large portion of contemporary physics; such a task would require volumes. However, it is possible to convey the nature of at least some of this research by sketching a few of the advances.

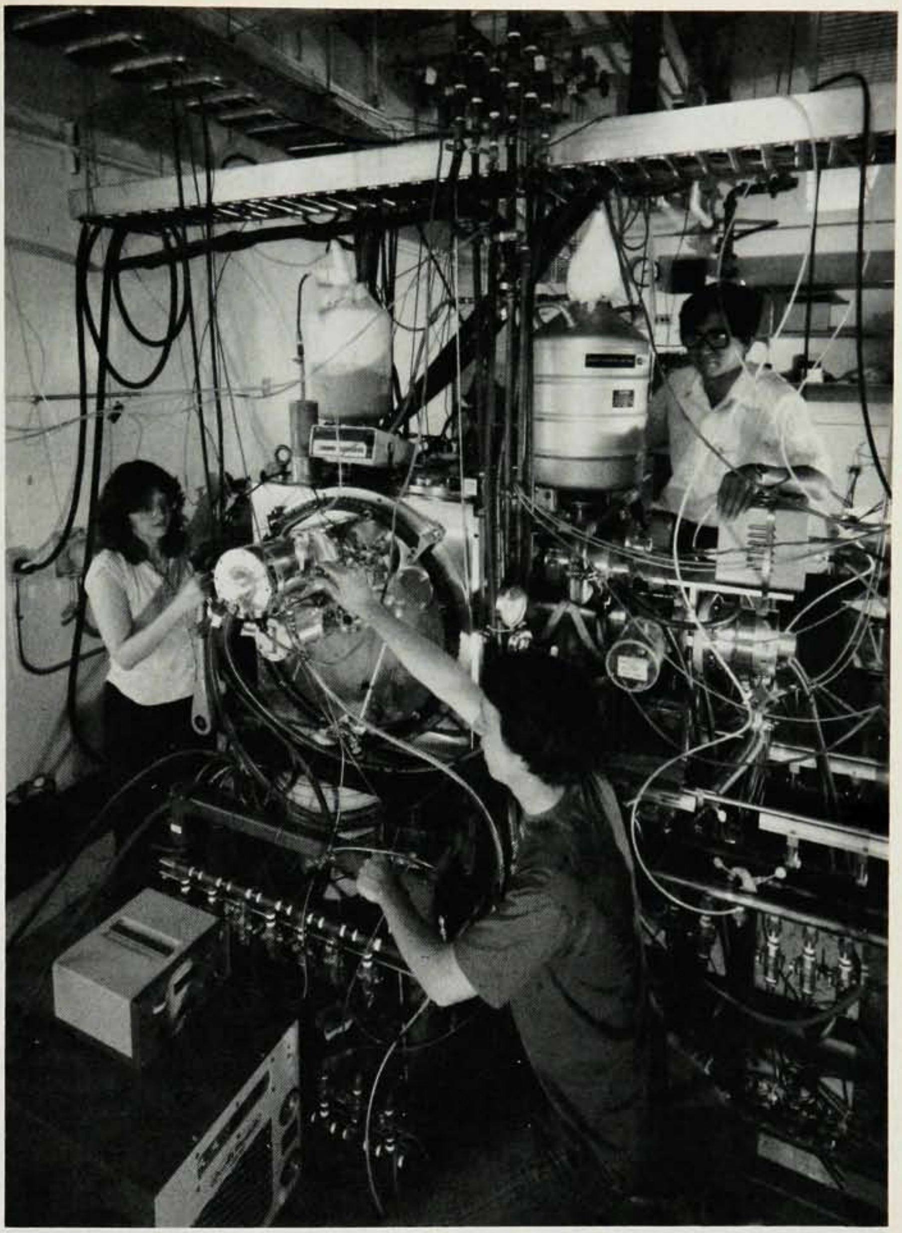
Small physics progresses by numerous experimental discoveries and the close interplay of experiment and theory. For example, meticulous studies of phase transitions in systems ranging from ferrites to gels have culminated in the creation of a fundamental theory of phase transitions—the renormalization-group theory. Experimenters have created new states of matter: a superfluid Fermi liquid, compounds in which electrons simultaneously occupy two valence states, one- and two-dimensional systems, new phases of liquid crystals and many others. Discoveries include the quantized Hall effect—two-dimensional quantum-mechanical phenomena manifested by real materials—and the fractional Hall effect—the signature of a totally unexpected electron gas condensate (see PHYSICS TODAY, June 1981, page 17 and July 1983, page 19). The development of techniques to create controlled disordered systems such as spin glasses has led to a new appreciation of random systems and the first clear picture of motion in random potentials. The discovery of new nonlinear phenomena, such as solitons and strange attractors, has vastly broadened our understanding of nonlinear dynamics and has found applications in topics as diverse as atmospheric turbulence, population dynamics and ventricular fibrillation.

Lasers have revolutionized spectroscopy. They have made it possible to create and study large classes of atomic and molecular systems and to witness multiphoton processes never before seen. Molecular ions, which play key roles in both interstellar chemistry and combustion, have for the first time been studied comprehensively. The flow of energy when two molecules collide can now be traced at the quantum level. New techniques for studying single electrons and ions allow measurements of the fundamental constants with unprecedented sensitivity and precision.

Small physics plays a central role in generating and elucidating fundamental physical and mathematical concepts. The renormalization-group theory, for instance, uses techniques developed in relativistic field theory. Out of this work grew the modern theory of phase transitions and fluctuations. The theory of phase transitions, in turn, is an essential ingredient for understanding the earliest stages of the universe as taken from contemporary ideas in cosmology, particle physics, and statistical mechanics. To cite another example, the concept of broken symmetry was developed independently in condensed-matter physics and particle physics. The acquisition of mass by a particle in a state of broken symmetry is manifested in superconductivity through the Meissner effect; in gauge theories it is manifested by the Higgs mechanism.

Some of the most demanding tests of quantum electrodynamics lie in extremely precise measurements in atomic physics. The interplay of experiment and theory in this area represents one of the most relentless confrontations of experiment and theory in all of physics. Quantum electrodynamics is the prototype of gauge theories; the search for its limits of validity bears on our understanding of the electroweak theory, quantum chromodynamics and other gauge theories. Other precision experiments have set limits on the isotropy of space, the possible breakdown of symmetries such as time-reversal invariance, and the validity of the principle of equivalence.

Technical as well as conceptual links join small physics to other areas of science. Magnets developed from research on high-field superconductors have made possible a new generation of accelerators. Atomic clocks are essen-



Molecular physics. Yuan T. Lee (background), Laurie Butler (left) and Alec Wodtky at Lawrence Berkeley Laboratory are shown with an apparatus used to measure the energies of the fragments of a molecule when it is dissociated by laser light. Such photofragment spectroscopy allows the study of molecular reactions starting from a moment when the reacting species are close together in a precisely defined quantum state. (Courtesy of Yuan T. Lee.)

tial in very-long-baseline radioastronomy; laser interferometers have opened the way to a new class of gravitational-wave detectors. Laser light-scattering spectroscopy is being applied to problems in physics, chemistry, biology and medicine.

These examples, which are drawn from only a few of the many active fields of small physics, illustrate the importance of discoveries in small-scale research to the advance of physics. These examples do not, however, begin to suggest the scope and rapid development of new front-line areas. Many subfields have sprung into existence or have rapidly grown into major research areas within the past decade. The list includes:

▶ *Surface physics.* A host of new techniques has opened the way to studying surfaces and surface phenomena: ultra-high-vacuum methods, tunneling microscopy, x-ray scattering from synchrotron sources, ion scattering, supersonic helium scattering and laser spectroscopy. There have been comparable theoretical advances, some resting on new numerical techniques. The research is advancing rapidly on the structure and excitation of surfaces, surface reactions and catalysis.

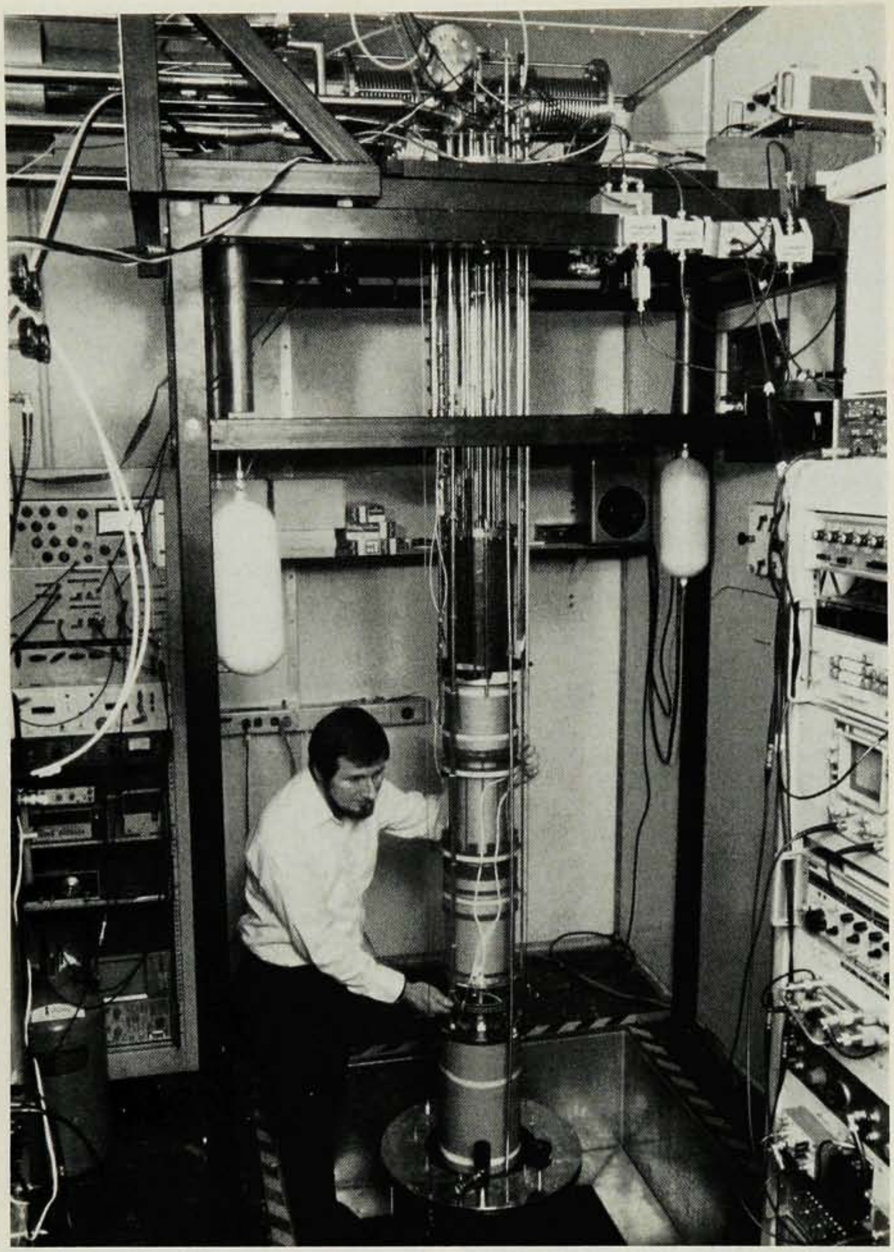
▶ *Artificially structured materials.* Molecular beam epitaxy and other techniques make it possible to create materials that are controlled on the atomic scale: superlattices composed of alternate layers of ordered crystals, amorphous layers that are disordered in two dimensions but ordered in the third, and systems that are effectively one-dimensional, such as those obtained by ion milling and other submicron machining techniques. Such materials, have properties found nowhere else in nature.

▶ *Clusters.* Using supersonic molecular beams, it is now possible to create clusters of atoms or molecules in sizes up to hundreds of particles. These clusters provide the opportunity to observe how matter organizes itself as it evolves from single particles into solids, and how atomic and molecular properties manifest themselves in condensed matter. With metal clusters we can see how band structures develop with increasing size, and we can witness catalytic and other surface phenomena.

▶ *Femtosecond spectroscopy.* Light pulses as short as 12 femtoseconds (12×10^{-15} seconds) have been generated, allowing the observation of the dynamics of molecules and solids at time scales never previously approached. In principle, one can take a "snapshot" of a molecule while it vibrates, witness how electrons in a semiconductor equilibrate or see how chemical reactions take place in solutions and in biological systems.

▶ *Nonlinear optics.* Nonlinear optical techniques have opened new areas in spectroscopy and have also made it possible to study atoms and molecular collisions in ways never before possible. Multiphoton processes, ultrasensitive detection, optical harmonic generation and laser cooling of atoms and ions are some of the advances made possible by nonlinear techniques.

▶ *Polymer physics.* The new ideas emerging from the theory of phase transitions and critical phenomena, combined with such experimental methods as laser light-scattering spectroscopy, nuclear magnetic resonance



Ultra-low-temperature physics. Dilution refrigerators have extended the frontiers of low-temperature physics into the submillikelvin region. This cryostat, shown with Douglas Osherhoff at AT&T Bell Labs, can reach temperatures of less than 100 μK. The cryostat is currently used to study the A_1 phase of superfluid He^3 and nuclear antiferromagnetism in solid He^3. (Courtesy of Douglas Osherhoff.)

and neutron scattering, have profoundly affected our understanding of the processes of polymerization and self-assembly of natural and synthetic macromolecules. These systems, consisting of polymers, micelles, macroemulsions and liquid crystals, are of central importance in many industrial, biological and physiological processes.

This "sampler" should give some idea of the great breadth and rapid progress in small-scale research. A broader portrait of these activities will be presented in the volumes of the *Physics Survey* that will be published shortly by the National Academy of Sciences and the National Research Council.

Impact on society

To appreciate the impact on society of research in small physics one need only think of what the world would be like if the transistor had never been developed. It would be a world without microprocessors, computers and the vast network of data-processing equipment on which science, governments and businesses depend, a world without instantaneous global communications and without the countless feedback and control devices that are essential to everything from jetliners to pacemakers.

Many of these developments emerged from basic research by small groups in industrial laboratories. These laboratories account for about 30% of the basic condensed-matter research in the United States. The strong coupling between industrial and university groups is one of the strengths of these research communities in the US, contributing to the advance of basic physics and the creation of new technologies.

Technology. The returns to society from small-group research can be prodigious. For example, magnetic-resonance imaging is widely regarded as the most important advance in medical diagnosis since the discovery of x rays. Magnetic-resonance imaging was made possible by research on nuclear resonance in chemical and biological systems, the development of superconducting magnets, theoretical research on tomography and image reconstruction, advances in numerical processing and high-speed data-processing devices, and, underlying it all, the discovery of nuclear magnetic resonance decades ago.

The laser has had an enormous impact on science and society. Today these devices are employed in nearly every area of physical science, as well as in the biological sciences and in medical research and therapy. Remote sensing with laser light is used to monitor pollutants, to analyze combustion and to study the atmosphere; laser metrology is used for high-precision surveying, for aligning accelerators and highways, and for controlling scientific instruments and machine tools.

The laser and modern optics play major roles in technology and industry. Fiber-optic cables are revolutionizing data transmission and long-distance communications. Laser printing has become a multibillion-dollar business. Laser-assisted manufacturing is increasingly employed in industry. Laser machining is ideally suited to robotics; it has been estimated that within a decade lasers will be involved in 30% of all the manufacturing operations in the US.

In addition to contributing to basic understanding of nature, small physics is vital to our national programs in defense, energy and the environment.

Education. Over half of the nation's PhDs in physics are trained in condensed-matter physics and atomic, molecular or optical physics. When the other small research activities are included, the fraction is over 70%. Thus the nation depends on small research groups to train most of the physicists who will carry forward basic research, execute the national programs and generate the new technologies that are essential to industry.

Students who carry out an experimental thesis in one of the independent groups usually acquire expertise in many areas. In atomic physics, for example, it is not unusual for a student to become highly skilled in mechanical and vacuum design, electronics, optics and lasers, computer hardware and software or numerical analysis; the student may also have acquired specialized skills in molecular-beam techniques, charged-particle optics or cryogenics. Other fields involve a different mix of skills, but every field of physics where a student designs, constructs and operates a piece of apparatus produces physicists with a broad range of basic skills who can move rapidly in new directions.

Priorities in big and small physics

The decision to construct a major research facility or to embark on a large research program generally requires a consensus within the pertinent research community. Typically this is achieved through debate and discussion conducted by an oversight committee or special panel. The debate may become heated, for different options often appeal to different segments of the community, but if the panel does its work well it will emerge with a prioritized list of the field's needs. These priorities define the major line of scientific development in the years to come, and they provide the funding agency with a reasoned request for the needed support. Time and again this process has helped the fields of big physics to move forward.

The process of setting priorities in small physics is less visible. Because these fields generally advance in many directions simultaneously and change rapidly in response to new opportunities, attempting to forecast the most promising new lines of research is not likely to be productive. Even a cursory look at the advances in the past decade reveals important developments that had not been—and could not have been—anticipated in the early 1970s. Thus priorities in these areas cannot be identified by a short list of topics in order of preference. Furthermore, most of these fields are supported by several agencies, sometimes without much coordination between them. There may be no "champion" agency to push vigorously for the priorities even if they could be succinctly identified.

Nevertheless, the independent research groups do set priorities. The process, though not as formal as in big physics, is just as demanding. The priorities are set by the individual researchers, who respond to intellectual challenges as new concepts emerge and new technologies become available, and by their peers, who must give their approval before most agencies will grant funds. Peer review can be a harsh arbiter, particularly when support is short.

Strong evidence for the effectiveness of this priority-setting process can be found by comparing the present "hot topics" with those of ten years ago; the list has changed significantly. The large number of new subfields—some of which were described above—provides a clear picture of how small physics sets its priorities.

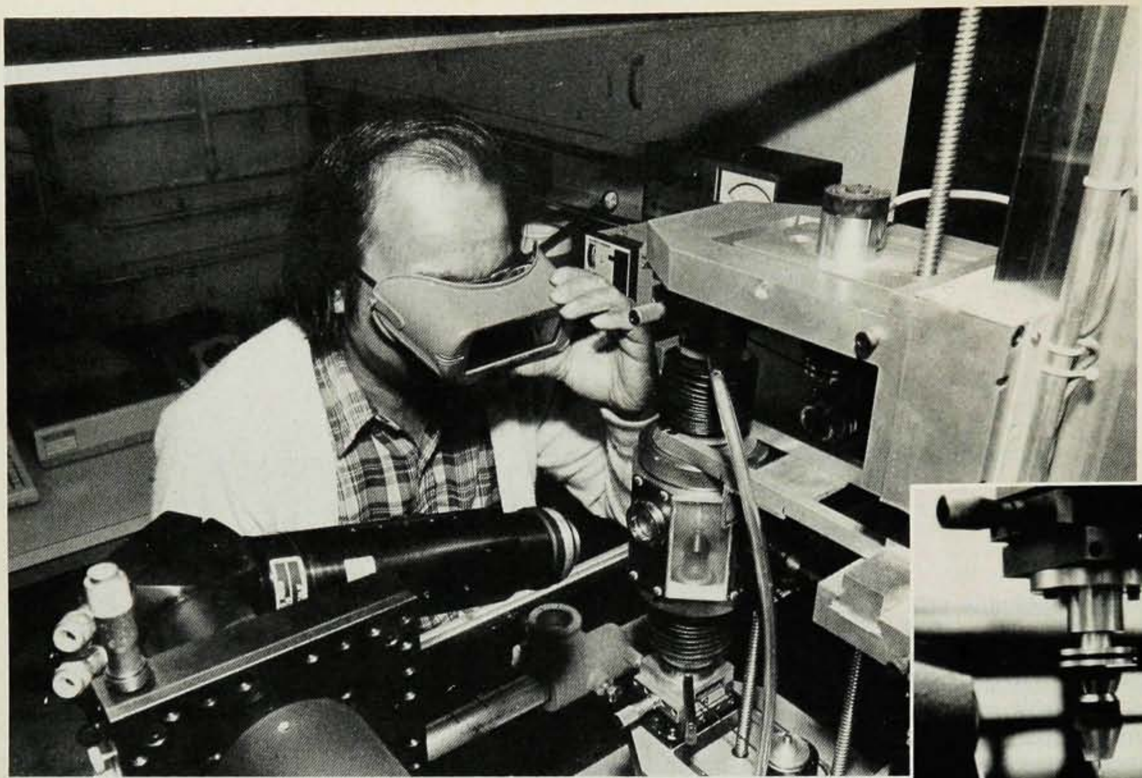
Concerns for the future

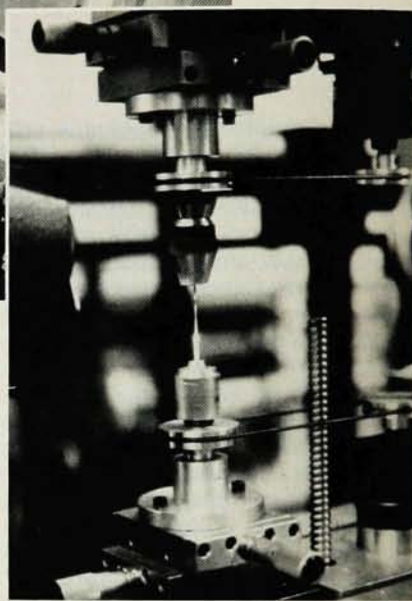
In times of cutbacks in the support of science, the small research groups can adapt rapidly to changing conditions. The scope of the research may be diminished and progress may be retarded, but one is not faced with the trauma of closing an existing accelerator or canceling a proposed one. Being small and flexible appears to be an advantage—but it has its dangers. One has an advantage in dealing with short-term cuts in support. However, in a prolonged period of scientific austerity, as we experienced throughout the 1970s, the independent research groups are vulnerable to being slowly starved for support by having to adapt to a pattern of chronic underfunding. The problem of deteriorating support is aggravated by the fact that much of the funding is subjected to the vagaries of mission-oriented agencies, which are neither directly responsible for basic research nor accountable to the basic research community. There is no mechanism for assuring continuity of research when an agency loses interest.

The most conspicuous evidence of serious trouble in small-scale research is the critical shortage of instrumentation in the university laboratories—a problem that has been widely noted.[2] Essential instrumentation in university laboratories is often obsolete or simply missing. The research is being seriously retarded; university groups are being excluded from new research areas. Molecular-beam epitaxy, for example, an important technique for making artificially structured materials, is pursued in many industrial laboratories but in few universities. The $1-million price tag for a molecular-beam epitaxy machine is too high for most research programs.

The DOD–University Instrumentation Program provides a perspective on the problem. In the first year of this five-year program, budgeted at $30 million per year, the requests were over $645 million. Estimates place the total need at over $1 billion.

There are other signs that the climate for small-scale research in the US





Single-crystal fibers. By continuously drawing material from a "button" heated by a sharply focused CO_2 laser (insert), single-crystal fibers can be created from sapphire and many other compounds. These crystals, which are among the most perfect ever produced, make it possible to study fundamental processes such as eutectic solidification and the growth of metastable phases. The high growth rate and ease of operation make possible rapid surveys of new materials and can provide novel types of fibers for optical devices. The apparatus shown here is in the laboratory of Robert S. Seigelson at the Center for Materials Research at Stanford University. (Courtesy of Roger K. Route.)

is deteriorating. Machine shops and electronics shops have been shut down in universities across the nation, and specialized services, such as crystal growing and materials preparation, have been terminated. Forefront research requires a healthy infrastructure of these services; their disappearance is symptomatic of chronic underfunding.

The low number of US graduate students is an additional reason for concern. Although the total of PhDs graduated each year has remained relatively constant for almost a decade, the number of US students has been falling. Forty percent of the entering students are now foreign (see PHYSICS TODAY, September, page 74). The reasons for this are complex. Most US graduate students are supported through grants to the independent research groups, while many foreign students are supported by their home governments. Furthermore, when students see that their professors are unable to purchase vital equipment, to support graduate students, postdocs, visitors and technicians, or even to travel to meetings, they will move to other fields. There can be no doubt that the low funding levels for the independent research groups are a contributing factor to the declining trend in US enrollment.

The picture of postdoctoral employment in the US today is particularly revealing; the *Physics Survey* reports that more than half of the postdoctoral researchers are foreign. These researchers, many of them supported by their own governments, are welcome guests in US research groups that lack funds to support US physicists.

The United States gains much from the foreign students and postdoctoral workers who participate in research here. Furthermore, their training often constitutes a highly cost-effective form of assistance to their countries of origin. Nevertheless, the relatively small number of young US physicists is obviously a source of concern.

There are other underlying problems, though they are harder to quantify. Academic careers involving small-scale research are significantly less attractive today than in the past. Although the number of academic openings is not large, many universities are finding it difficult to fill them with qualified candidates. The universities have lost much of their ability to compete with industrial laboratories. Salary can be an important factor, but the decisive factor is often that the industrial laboratory can provide the resources to move the research ahead rapidly while the university cannot. The demand for academic physicists is expected to increase sharply in the 1990s. Unless the climate for support improves, there will likely be a severe shortage of qualified candidates in universities throughout the nation.

Collectively these problems are cause for deep concern over the future of small-scale research in the United States and the future of physics in our universities.

The cost of small physics

There is wide misconception about the cost of small physics. Even small equipment is expensive. An electron-beam scattering apparatus can cost \$200 000; a tunable laser system, \$150 000—and many experiments use more than one laser. A dilution refrigerator costs \$200 000; a molecular-beam epitaxy machine, as mentioned, can cost $1 million or more. Setting up a typical small laboratory can cost anywhere from a few hundred thousand to over a million dollars; if the research requires services such as materials preparation, the setup costs can be much higher.

Operating an independent research group in a university requires support for graduate students, postdoctoral workers or other research staff, technicians, materials and supplies, and support for the up-to-date equipment. Total costs vary from field to field, but an active university research group can require $200–$400 thousand per year; many groups need much more.

Most of the research support in the US comes from the Federal government. Federal grants supporting experimental research in small groups are generally well under $100 000 per year—far too little to meet the actual costs of the research. Many groups are thus forced to apply for several grants. Physicists spend valuable time searching for support, preparing proposals and juggling budgets between various grants. The time they can spend with students is being diminished; their research is slowed down. This pattern has corrosive effects in laboratories across the nation. Small research groups have lost much of their capacity to pursue new ideas vigorously and to move in new directions.

The large difference between the size of the research grants and the costs of the research threatens the future of the small independent research groups in the US. After a decade of severe winnowing, attempts to direct funding to a smaller number of groups would do as much harm as good. Funding must be brought up to a viable level. Federal concern for basic research within the past few years has provided a favorable climate for addressing these issues. Recent sharp increases in support for some areas of basic physics are encouraging, but the overall situation for the small research groups continues to deteriorate.

A perspective on small physics

The many areas of research in small groups comprise a conglomeration of activities supported by different agencies for different purposes. There is no obvious way to judge the nation's need for any single portion of this research in the context of the total support for physics. It would be difficult, for instance, to attempt to balance the nation's need for low-temperature physics against the nation's need for a new accelerator.

However, if small-group research is viewed collectively, it assumes a clear identity in the world of physics and in the national scene. The small research groups produce much of our best science, and they train the majority of our graduate students; in addition, they generate much of our new technology. Thus these small groups constitute an invaluable resource for the nation.

One can obtain a reasonably clear picture of the national investment in small-scale physics by examining the support for research in the universities. In 1983 the Federal government is estimated[3] to have spent approximately $330 million in the universities for "research and development" in physics. This figure essentially represents support for basic research. Of this amount, approximately $280 million is estimated to be used for research by small groups.

Estimates on the need for support of small physics, based on material gathered by the Physics Survey Committee for its forthcoming report, appear to point to the same conclusion: For the research to move ahead effectively, this support needs to be roughly doubled over a period of perhaps four years. This would require that the nation increase the total investment in these areas by $70 million per year—in real dollars—for four years. In addition, a special infusion of support for instrumentation in university laboratories is needed urgently.

When one views small-scale research collectively and witnesses its enormous impact on science and its abundant returns to society, this research must surely represent one of the most cost-effective ways for the nation to invest in research. The cost of assuring the continued vitality of this research is modest compared to the total cost of modern physics; it is extremely small compared to the national expenditures for research and development based on the fruits of this research.

In the process of deciding the future direction of physics in the United States, the collective needs of the small independent research groups deserve to be considered in parallel with the needs for new accelerators and other major facilities.

* * *

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