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Research Instrument Sharing

Continued availability of advanced instruments must involve sharing; how are instruments shared?

Charles L. Coulter

Summary. Continued progress in many areas of science depends on access to advanced modern instruments and the data they provide. Costly instruments have been shared in a number of disciplines for many years, and common patterns of shared usage have developed independently. The scientific and financial aspects of large instrument usage are discussed from the points of view of the instrument centers, the users, and the funding agencies. The instrument problem is not one problem but many, and coordinated solutions must be implemented with well-defined goals based on knowledge of the needs of the users and developers of instruments.

Access to advanced instrumentation facilities is essential for the conduct of most research projects in the fields of physics, chemistry, biology, and biophysics and has been a key factor in most recent advances in basic research in the physical and biological sciences. Awareness of this dependence on instruments and the increasing difficulties in obtaining funds to replace and upgrade instruments has led to growing concern about the problems of effective support, management, and utilization of research instruments. The National Academy of Sciences (NAS), the National Science Foundation (NSF), the National Institutes of Health (NIH), and the Energy Research and Development Administration [now part of the Department of Energy (DOE)] (*1–7*) have all recently sponsored or carried out studies, both formal and informal, of the need for and management of costly instrumentation resources. In addition, a broader study (*8*) of the state of scientific research in U.S. universities drew attention to the increasing concern within a wide spectrum of university departments about maintaining up-to-date instrument facilities for both teaching and research. While good cases can and are being made for alleviating these problems by asking Congress and the appropriate granting agencies to provide more funds in existing and new programs, these cases could be supported by better characterizing the usage patterns for current instruments.

One aspect of the overall problem that has received little attention is the current effectiveness of shared instrumentation facilities in various settings. Are presently available instruments being used in an equitable and cost-effective manner? Do various disciplines have discrete types of users, or are there broad models for shared usage that cut across disciplines? In this article some aspects of instrument sharing in natural science areas are reviewed in order to identify common features of use and in general to better characterize the user communities. Several fields of science have been selected as examples for discussion on the basis of the need of research scientists in these disciplines for access to costly instruments and on the basis of differing patterns of shared usage in these areas.

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Digital computers were one of the earliest examples of essential equipment that was shared across disciplines, and over about 10 years elaborate support and access procedures were developed for computers in response to need, opportunity, and user pressure. Computer-use history thus will be a good starting point for this discussion. High-energy physics has been the focus for nationally and internationally shared resources for many years, both in the United States and in Europe. This sharing began in the universities and has expanded to include national laboratories and international consortiums such as the European Organization for Nuclear Research. Chemistry requires extensive service instrument facilities in addition to research instruments that are more selectively shared, since most compounds are identified and assessed for purity by means of spectroscopic or other instrument-related parameters. Biophysics and cell and molecular biology share facilities for animals and for cell and tissue growth and separation, but are not as accustomed to sharing research instruments widely.

Digital Computers

Computer centers were widely developed in the 1950's and represent an early example of interdisciplinary sharing of equipment. The initial users of computers came from physics, mathematics, chemistry, and the engineering sciences; applications were primarily in areas involving difficult computations and the mathematical manipulation of limited data sets. Scheduling was casual and services were limited or nonexistent. The development of more advanced and reliable machines and of the Fortran language compiler (*9*) by the International Business Machines Corporation and of other advanced languages such as Algol (*10*) made the computer much more widely available to physical and social scientists and to researchers in areas such as management science and economics. More formalized mechanisms for scheduling and for training and programming assistance were instituted in response to user pressures. Computer science departments also became more numerous and were frequently involved with the development of higher-level languages and new problem areas. Batch-processing systems with sequential job queues and little sharing of space within the central computer were optimized through a variety of systems organization mechanisms in the 1960's. In parallel, and in part as a result of these developments, the concepts involved in time-sharing on computers were developed and implemented in selected centers, sowing the seeds for present-day remote access time-sharing systems linked through telephone lines. There are now many regional and some national networks such as ARPANET and TYMNET. Current user patterns span all the areas above, from network access to batch systems and personal minicomputers located in the laboratory.

Fiscal practices in computer centers have had difficulty keeping pace with the changes in technology. Initially, maintenance and upkeep costs in university computer centers were handled either through grants or by the parent institution. Fee systems were subsequently introduced with the cost dependent on the priority for running the job, but these virtually never led to complete cost recovery. The need to underwrite deficits in central computer centers remains a difficult problem in universities that went into the buying or leasing of very large machines. When used effectively, large computers offer a sizable cost saving per hour of use, but the capacity of most of these machines may well exceed the need or user funds within a particular research institution. Unused capacity on modern, high-throughput equipment is both a fiscal and a scientific problem and is found in many disciplines (*3*, p. 8). For computer centers, the problem was exacerbated through administrative efforts to satisfy widely varying needs equally well in one center. The universities attempted to solve this problem, with limited success, by selling time on their equipment to other academic and private users and, with more success, by integrating the computer into the educational curriculum, but this introduced priority constraints that further complicated the management problem. The trend away from centralized general-purpose computer centers makes these problems less critical.

High-Energy Physics

Physics was the first disciplinary area to make wide use of shared resources. Ernest O. Lawrence conceived the cyclotron principle for accelerating particles about 1928, and an 11-inch cyclotron was functional in 1932. By 1939, when Lawrence received the Nobel Prize in physics, the radiation laboratory of the University of California at Berkeley had published 163 papers with 76 different authors (*11*). The radiation laboratory had a core of onsite research groups and numerous visiting scientists. This model has persisted with other accelerators, storage rings, neutron sources, and the like. The Stanford Synchrotron Radiation Project, for example, began in 1974 as a national facility operating in parallel with the high-energy physics colliding beam research on the storage ring at Stanford Linear Accelerator Center (*12*). By 1976, there were 165 users involved in 85 proposals from 34 institutions. A policy board, appointed by the president of Stanford University, provides overall advice to the director, and proposals for use of the facility are reviewed by a separate panel. Organizations making major capital contributions to the facility are granted a period of priority use, after which the equipment is available to others. Beam time is free, but users must pay for necessary support services. The Lawrence model of strong core research groups and international usage by visiting scientists has proved to be very successful and, with some variations, is used worldwide. Separate travel and usage grants exist in many cases to facilitate use by outside investigators.

In the United States the Department of Energy funds 25 laboratories and research centers, some of which function as national resources in basic and applied research (*13*). These include both single-facility laboratories such as Stanford Linear Accelerator Center and Fermi National Accelerator Laboratory and laboratories with broader missions such as Argonne National Laboratory, Brookhaven National Laboratory, and Los Alamos Scientific Laboratory. Typical research enterprises in these laboratories include a core research group with a number of visiting scientists doing collaborative projects. For the Zero Gradient Synchrotron at Argonne, for example, there were three groups on site concerned with operations, high-energy applications, and future accelerator design, along with a large number of outside users. Time for both internal and external users was assigned by a committee made up of both outside users and Argonne staff. The facilities at national laboratories are unusual and in some cases unique, and the experiments are highly sophisticated. Service (*14*) is a minor aspect of these efforts and is usually carried out at true cost on a fee basis. The division of effort between basic and applied projects is different in each laboratory, and only some of the projects within each laboratory involve outside collaboration.

Chemistry

A report on opportunities and needs in chemistry by the Committee for the Survey of Chemistry of the NAS was published in 1965 (*1*) and had a noticeable impact on research support in chemistry. In 1971 a survey of equipment needs in a number of academic disciplines, including chemistry and biochemistry, was carried out by the NAS and the NSF (*2*). The NSF also sponsored an in-depth study of the distribution of major instruments in chemistry in the United States and of the funding and management practices involved in instrumental support of chemical research in the United States and selected foreign countries; the results were published in 1975 (*3*). These reports are the basis for this discussion.

The chemical research community is characterized by a strong need for analytical service support, since instrument-related parameters are the primary means for identifying compounds and reaction products and assessing purity. In part because of this dependence, it also shoulders an unusually large share of the burden for developing new instruments and modifying older instrumental approaches to chemical research problems. The latter function brings academic research scientists into close contact with instrument companies, and both characteristics are reflected in relations with industrial and nonprofit research establishments, which are the main users of the educational products of the universities—Ph.D. research scientists. The main instrument areas involved in chemical research are spectroscopic, including mass spectrometry, nuclear and electron spin resonance, and infrared, ultraviolet, visible, and Raman spectroscopy; kinetic, including stopped flow, laser, and temperature jump systems; and diffraction, including x-ray, electron, and neutron diffraction equipment for studying solids, liquids, gases, and solutions.

The impact of NSF and NIH programs on chemical instrumentation centers was examined in a report by Walling *et al.* (*3*), and some of the conclusions of that report are relevant to the current discussion. The authors distinguished two rather distinctive types of instrumental laboratories that have developed in the United States—departmental instrument centers and instrument research centers. The former laboratories are maintained to support the research of a sizable group of faculty and students within a department, and correspond roughly to a central analytical laboratory in an industrial research organization. They include a variety of sophisticated modern instruments with technical supporting staffs, and are designed to meet routine service needs efficiently and effectively in most cases. The instruments are acquired from NSF on a shared-cost basis or with university or private funds. The survey conducted in connection with the Walling report indicated that these departmental instrument centers possessed considerable unused capacity, and in some cases were shifting toward providing services to outside users (*3*, p. 8). Instrument research centers are operated by one or more instrument research specialists and are devoted primarily to advancing instrumental analysis. Such centers are not usualy efficient sources for routine service, but are very effective in engendering collaborative research between well-qualified scientists with limited instrumental background and instrument specialists. The Biotechnology Resources Program of NIH supports several centers of this type in the area of biophysical chemistry. From the point of view of instrument sharing, these examples highlight the service and collaborative usage patterns common to much of chemical research.

Financially, all centers investigated during the NSF study were subsidized through grants or departmental funds. User fees were frequently charged for routine service use of instruments, but these fees rarely sufficed to cover operating and maintenance costs, let alone amortization of the equipment. The Walling report presented some realistic cost estimates for nuclear magnetic resonance (NMR) and mass spectrometer usage and made a number of detailed recommendations regarding fee and support mechanisms. For a 25-megahertz carbon-13 NMR instrument operating in the Fourier-transform (FT) mode, $27 per hour was the estimated true operating cost. For mass spectrometry, costs ranged from $80 to $200 per hour, depending on the resolution and special ionization conditions needed (*3*, p. 32). In England, the National Physical Chemical Measurement Unit is a service-oriented facility operating on a fee basis. A ^{13}C FT spectrum was billed at £48.50 per hour as of 1974, and a low-resolution mass spectrum at £34.50 per hour, with the fees supplied through Science Research Council grants to the users (*3*, appendix D). Instruments are not free and will rarely be self-supporting either alone or in groups. Both funding agencies and users should recognize this and work together to place instrument provision, maintenance, and use on a sounder financial base.

Biophysics

Biophysics is a multidisciplinary science through which the methods of physics and chemistry are applied to biological systems. It shares with biochemistry a major interest in molecular biology and includes substantial subgroups in protein crystallography (*4*) and electron microscopy (*7*, *15*). Shared usage of instruments is less formalized than in chemistry, and the service load on instruments is modest. Liquid scintillation counters, centrifuges, and some types of chromatographic and electrophoretic equipment are often shared within a department. Interdisciplinary collaboration is common both within biophysics departments and with scientists in related disciplines in other departments. Biophysicists share with chemists an interest in and responsibility for developing new or modified instruments suitable for use with biological molecules and systems. The specific needs of biophysicists are encompassed in those of chemists and cell and molecular biologists in general.

Cell and Molecular Biology

Biologists have long been accustomed to sharing animal quarters, specimen preparation equipment for light and electron microscopy, and cell growth and separation facilities but have been less accustomed to sharing instruments (*2*, attachment A, p. 28). Light microscopes are relatively inexpensive and widely available; specialized microscopes for interference or phase-contrast studies are usually shared but not widely used. The primary large instrument involved in cell biology research is the electron microscope, and sharing of this instrument is very selective. Maintaining a transmission electron microscope in peak operating condition for high-resolution microscopy requires careful use by experienced personnel. Scanning electron microscopes are less sensitive and have fewer specimen preparation problems at the usual rather low resolution, and they are frequently shared (*2*, attachment A, p. 28). The scanning microscope usage involves some service, but in general sharing in cell and molecular biology is done through individual collaboration between scientists with common inter-

Table 1. Assessment of current user needs by discipline.

Community needs	Discipline			
	Physics	Chemistry	Biophysics	Biology
Analytical service	Low	High	Medium	Low
Visiting scientist	High	Low	Low	Medium
Interdisciplinary collaboration	Low	Low	High	Medium

Table 2. Suppliers of user needs.

Community needs	Supplier		
	Universities	National laboratories	Industry
Analytical service	Medium	Low	High
Visiting scientist	Medium	High	Low
Interdisciplinary collaboration	Low	Medium	High

ests. With the exception of the scanning electron microscope facilities, fees are virtually never charged. Maintenance of the centralized equipment is subsidized by the major users through their individual research grants or by the department. Molecular biologists need spectroscopic equipment, which is shared in some cases, and microbiological equipment for handling bacterial and eukaryotic cells. Recent scientific interest in recombinant DNA research has focused attention on the need to share facilities for studying novel bacterial systems. The research equipment for such studies is inexpensive, but containment facilities are costly.

Instrument sharing in biology thus is centered on advanced microscopes. These include conventional scanning electron microscopes, high-resolution scanning electron microscopes, medium- and high-voltage electron microscopes, and electron probe systems that can provide maps of the location and concentration of elements within specimens. The NIH, NSF, and DOE have supported the development of some of these instruments through research project grants, and support regional or national facilities that make one or more of each of these instruments available to outside users. Service remains a minor and difficult area even on the shared instruments, since most of the scientific problems studied by electron microscopy depend heavily on experimental design, control experiments, and specimen preparation and staining techniques. Financially, the government supports most of these large instruments (with the exception of some scanning microscopes) and such support will be required for some time to come. A rough cost analysis (*16*) suggests that a 2-week project on a medium-voltage electron microscope (500 kilovolts) costs $10,000; use of a high-voltage electron microscope would increase this cost because of the higher initial investment. These correspond to estimated hourly costs in the rage of $150 to $300.

Supply and Demand

To focus the discussion, a rough summary of the variation of user needs by discipline is shown in Table 1. Service needs are highest in chemistry and increasing in biophysics and biology. As cell biology becomes more quantitative, shared service will extend well beyond the current rather limited group of shared instruments. Departments with major cell biology interests may have to learn to accommodate and administer major new instrument facilities, which would have to be widely shared; cell sorters, for example, are now available, in demand, and can be shared. This accommodation is, in part, a sociological problem that has been faced by other departments in other disciplines. Chemistry departments assimilated computer-controlled x-ray diffractometers into their general research environment in less than 10 years and now provide research service facilities in this area in some cases. More awareness of the common threads in the fabric of research science should help the development of equitable and satisfactory solutions to changing requirements. Physics has always used the visiting scientist model of shared use extensively and is expected to continue to do so. More formalized mechanisms for access to large facilities serve to bring in young as well as established investigators. Biologists make reasonable use of the visiting scientist mechanism to learn new experimental techniques by traveling to the originating laboratory. Interdisciplinary collaboration is found more frequently in the biological sciences than in the physical sciences, in part because detailed understanding of the biological system being studied is needed to fully evaluate the results. For costly shared instruments, the balance between broad support access and effectiveness in terms of optimum use of these instruments is a delicate one.

If we estimate the degree to which research establishments are providing for the various user needs, as in Table 2, we see that analytical service needs are best met by industry. Chemistry departments have significant service needs and facilities and also do well, with a looser management system, in meeting service needs. National laboratories strongly favor the visiting scientist arrangement for collaborative work. Such laboratories have specific missions, and visiting scientists can be selected to contribute to the fulfillment of those missions. For similar reasons, interdisciplinary collaboration is also common in national laboratories. Industry, for proprietary reasons among others, does not cater to the visiting scientist mode. Interdisciplinary collaboration does play a large role in both basic and applied industrial research, however, and centralized administration permits tight control over research costs and little duplication of facilities.

Support Programs

The above rather limited summary of user needs and institutional services provides a basis for examining the current support programs that are providing instruments to serve these needs. Two federal programs have been chosen for examination as the main grant programs with multidisciplinary impact for which data are available—the Chemical Research Instrumentation Program of NSF and the Biotechnology Resources Program of NIH. Both of these programs focus primarily on universities: this restriction seems appropriate, since universities and colleges accounted for 55 percent of the total basic research funds in 1976 (*8*, p. 20).

The NSF has long recognized the special instrumentation problems of chemical research, and since 1957 has made substantial contributions to chemistry through the Chemical Research Instrumentation Program of its Division of Chemistry. The NIH has also contributed for many years toward instrument development and accessibility for selected biomedically related areas of

chemistry as well as for biology and medicine; the development support has primarily come from the National Institute of General Medical Sciences, and broader facility support from the Biotechnology Resources Program of the Division of Research Resources. The latter program provides access to advanced instruments and technology on the basis of problem area rather than department or university affiliation. Several other federal agencies under the Department of Defense, the National Aeronautics and Space Administration (NASA), and the Department of Energy have provided long-term instrumental support.

Chemical Research Instrumentation Program

The NSF Division of Chemistry and its advisory panels recognized the need for broad-based instrumental support in chemical research in the early 1950's. In 1957 the Chemical Research Instrumentation Program was started in response to these recognized needs for major chemical instruments for research and training (*17*). The initial budget for the program was about $300,000, and 39 grants for instruments costing $5,000 or more were made on a 50 percent cost-sharing basis in 1957. The annual budget rose to a maximum of $4.3 million in 1968, and currently is about $2.6 million. From 1957 to 1977 903 grants were awarded for a total of $33.5 million. These funds were for capital equipment only, and until recently were only awarded on a 50 percent matching basis; the strict cost-sharing conditions have now been relaxed somewhat because of increasing fiscal constraints in universities (*8*, pp. 19–45), but the recipient department or institution still must provide about 40 percent of the funds for the equipment. The grants are for chemistry, and in a few cases for biochemistry or a related department, and must involve two or more research groups as major users; in practice, five or six principal user groups are typical. The number of users and the quality of the research to be done on the instruments have always been major factors in reviewing requests; statements regarding maintenance, operational staff, and access arrangements for other users have also been part of the application. In recent years, more detailed information regarding fund sources for maintenance and support personnel have also been required. Fees are not, as a rule, charged, but this is left to the discretion of the department involved. The chairman of the department requesting the equipment is the principal investigator and is responsible for the availability and equitable use of the facilities. Some of these grants have been jointly funded with other divisions of the NSF, or with NIH, DOE, or other federal agencies.

The program has been the cornerstone of instrument-related chemical research for many years. Because of the cost-sharing requirements, the $33.5 million in public funds have provided over $60 million in major equipment, much of which is still in use today in departments of chemistry throughout the United States. In recent years, some funds have also been used for individual equipment grants, and the Division of Physiology, Cellular and Molecular Biology of NSF has an equipment grant fund of about $500,000 per year, but these figures are not included as part of the Chemical Research Instrumentation Program. Maintenance, equipment amortization, user support services, and guaranteed access are aspects that each institution has had to develop and fund on its own, and the results are varied. As noted in the Walling report (*3*), the Chemical Research Instrumentation Program has provided absolutely essential analytical service support for chemistry and can take credit for maintaining chemical research at its current level of excellence for many years.

Biotechnology Resources Program

The Biotechnology Resources Program of the Division of Research Resources of NIH was started in 1962 as a separate program to oversee and manage biomedical computer center grants. In 1965 the program was broadened to include instrumentation centers in universities; by 1977, approximately $13 million per year in support was being provided to 18 computer resources, 3 biomedical engineering centers, 8 mass spectrometry resources, 12 NMR resources, 1 electron spin resonance (ESR) resource, 6 electron microscopy centers, and 4 other types of resources (*18*). Several of these resources are national in scope and each of them is characterized by having four identifiable research components: core research, collaborative research, service, and training. Some of these resources are jointly funded with other NIH institutes, NSF, NASA, or DOE. The mission of the program is to break new ground in biomedical research areas by providing regional or national access to highly innovative and in some cases unique instrumentation and technology for biological and medical scientists. A directory of the available resources with areas of service and contact persons has been published (*19*).

Table 3. User patterns by project in biotechnology resources. The data are for fiscal year 1977. Entries correspond to averaged percentages of projects in each area for each resource type.

Type of resource	*N**	Core projects (%)	Projects from same institution (%)	Projects from other institutions (%)
Computer	7	26	54	21
NMR-ESR	9	17	48	35
Mass spectrometry	8	10	44	46
Electron microscopy	3	37	27	37

*N, number of resources.

Table 3 summarizes the data for 1977 on outside use of these facilities; in mass spectrometry, for example, 46 percent of the projects were, in the average center, carried out by scientists from outside the host institution. Regional centers with less than 33 percent outside use tend to have difficulty getting strong endorsements for applications for continued support since their regional character is then open to question. Table 4 illustrates the overall time distribution within the same resources. Some of the centers especially for computers are highly specialized, and an accurate tally of projects and instrument time could not be determined from the annual reports, so these were omitted from Tables 3 and 4. Problems for collaborative research or long-term use are frequently screened and priorities set by an advisory committee set up by the resource; this committee also oversees the long-range planning for the resource. The similarity of the time distribution in various fields reflects, in part, the cooperative management of these resources by the senior scientist involved, the advisory committee, and the NIH staff.

After 10 years, the basic concept of setting up shareable resources under guidelines (*20*) requiring the four research components given in Table 4 is still viable and developing. Core research includes broad methodological and analytical techniques as well as in-

Table 4. Time distribution within biotechnology resources for 1977. Units are connect time (computers), instrument time (NMR-ESR and mass spectrometry), or beam time (electron microscopy).

Type of resource	*N*	Core research and training* (%)	Collaborative research (%)	Research service (%)
Computer	7	33	25	42
NMR-ESR	9	33	30	37
Mass spectrometry	8	33	44	22
Electron microscopy	3	60	18	22

*Less than 10 percent of the time used involves training in all cases.

strument research, and has been most effective when carried out in response to user-generated needs. Core research also includes the development of new instruments in some cases. Collaborative research and service as an area of contact with potential collaborative users are the heart of the program. In the ideal situation, which occurs with surprising frequency, the specialist at the resource becomes involved in helping a user with an especially difficult or new application; and the two of them, experts in their own fields, find the problem acquiring new depth and wide applicability as work goes on. A collaborative project or even a series of collaborative projects then results in favorable cases. Another common experience is that of the short-term or service users who find that a few experiments on a high-resolution or high-field instrument allow them to calibrate their system and refine their techniques so as to make more effective use of the less costly equipment in their own laboratory or institution.

Financially, the Biotechnology Resources Program funds equipment, maintenance, personnel, and core research costs from the inception of these grants. Average ongoing support levels for spectroscopy resources are about $100,000 to $150,000 per year in direct costs (*18*). Fees are often charged for services in mature resources, and a well-defined phaseout procedure has been developed to help place resources that no longer qualify for support on a self-sustaining basis. It is a credit to the program that several of the resources for which support was withdrawn over the past few years continue to function on an institutional and in some cases regional basis. Fees do not cover amortization of the equipment, however, so such success stories are likely to be of finite duration.

Discussion

Access to advanced modern instruments and the data they provide is an essential factor in the continuing effort to expand the frontiers of the physical and biological sciences. American leadership in many areas of science depends on such access; and the partnership between federal agencies, as representatives of the public, and research scientists and their institutions has indeed been fruitful. Maintenance and expansion of this necessary instrument base is a challenging problem, the solution of which must involve federal, state, local, and private actions. A coordinated approach to the long-range solution of this problem presupposes knowledge about how effectively instruments are now being used, and, in the case of very expensive instruments, how they are shared and financed. Common patterns of shared usage have developed independently in a number of disciplines. Recognition of these common features is important in considering current and future mechanisms for providing for shared instruments. Biologists in particular have an opportunity to build on the experiences of others in meeting these needs.

Financially, it is essential that research projects that require extensive access to costly instruments bear part of the financial burden for maintaining, upgrading, and, when possible, replacing these instruments. Requests for support of problem-oriented research of this type should provide evidence of the necessity for instrument access in the conduct of the work as a justification for such funds. Significant cost recovery would permit needed funds to be channeled toward pushing forward the frontiers of instrument development in both old and new fields. The computer center experience suggests that full costs will rarely be recovered on shared equipment, but significant recoveries are possible. It also suggests that trying to be all things to all users is not a likely path to success. User needs for shared instruments differ widely, and in meeting these needs access is not enough. One must also ask for what purpose and to what end, and the users must answer these questions. The efficiency, effectiveness, and breadth of usage of other instruments in many disciplines can and should be examined as a basis for coordinated action to maintain scientific excellence. The instrument problem is not one problem, it is many problems, and effective solutions must be implemented with well-defined goals.

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