Physics in perspective

The chairman of the National Academy of Sciences Physics Survey Committee gives a preview of the Committee's report, a kind of road map through the committee's recommendations.

D. Allan Bromley

Early in 1969, and as a consequence of extended discussions within and among the Committee on Science and Public Policy of the National Academy of Sciences, the Division of Physical Sciences of the National Research Council, the Office of Science and Technology, the President's Science Advisory Committee and several of the major federal agencies that support physics, a decision was reached to initiate a survey of the US physics enterprise. The completed report of the Survey Committee will soon be available. (See box on this page for table of contents.)

This report deals principally with the opportunities that physics faces during the 1970's. These opportunities are of several kinds: for fundamental new insight into the nature and causes of natural phenomena; for the development of new devices and technologies; and for greater service, both direct and indirect, to US society, of which physics forms an integral part. The problems addressed are largely those that we foresee in the realization of these opportunities.

In large measure these problems reflect significant changes that have occurred in recent years. Among these have been striking changes in the different subfields of physics, a marked change in the growth rate of federal support for physics, changes in many aspects of US society, changes in an ill-defined but none the less real ordering of priorities in the public mind and changes in both the academic and federal communities that have particularly affected the motivation and basic philosophies of much of a student generation.

D. Allan Bromley, who headed the committee that prepared the survey report, is chairman of the Yale physics department.

Why a new report?

These changes, too, provide much of the answer to the very real question: Why yet another major survey report on a scientific field? In 1966, under the aegis of the Committee on Science and Public Policy (COSPUP), a national committee chaired by George E. Pake published an extensive report on the status and opportunities of US physics entitled *Physics: Survey and Outlook*.

That survey was completed at a time when the growth rate of US science in general, and of physics in particular, was at an all time high and the field was in a state of robust health. Under these circumstances, and within the framework of a burgeoning national economy, it was not surprising that physics was considered in a relatively narrow context that justified extrapolation of the needs and objectives of the field on the basis of internal considerations and the anticipated exploitation of most of the new opportunities that the field then presented.

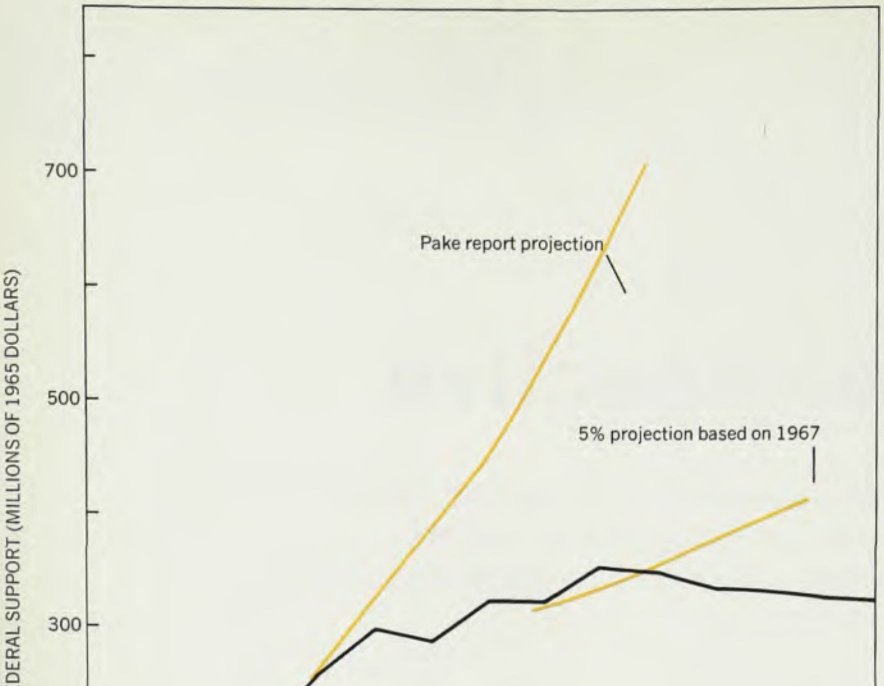
As is clear from figure 1 these extrapolations have not been realized. Although it is extremely important for physicists to continue to emphasize these potentials, it has become necessary to address the difficult question of priorities among and within subfields of physics. Many of the frontier areas of physics, because of the scope and scale of the activity and instrumentation required, are inescapably depen-

Physics Survey Report

Table of contents

The Physics Survey Committee Report will be available in midsummer, and two companion volumes containing the reports of the subfield panels will appear in late summer. All will be available from:

Printing and Publishing Offices
National Academy of Sciences
2101 Constitution Ave.
Washington, D.C. 20418



The predictions of the Pake report about US government support of basic physics were made when the growth rate of physics was at an all-time high. Actual federal support has in fact not even kept pace with inflation.
Figure 1

dent on federal support. And the competition for available federal support is increasing steadily as new attacks are mounted on major problems of national and social concern. Therefore, the Committee has attempted to define and develop contingency alternatives in an effort to ensure the most effective use of the available support throughout physics.

But there should be no misunderstanding: The opportunities and challenges for both internal growth and external service to society are still present; however, if current trends in the growth of support for US physics continue, only a few of these opportunities will be realized, and the relative position of the US in the international physics community will inevitably decline.

Physics has contributed and continues to contribute to society in a great many ways through its concepts, its devices and instruments and, more especially, the capabilities and activities of its people. Basic to the training of a physicist is the effort to reduce complex situations to their most fundamental aspects, so that they can be subjected to mathematical tools and the philosophic rigor of natural laws. The research style and approach that characterize the physicist frequently constitute his major contribution to attacks on problems outside his own specialized field. In the past, the training of a physicist was characterized also by a breadth and flexibility that permitted him to range widely in his search for challenging problems not only in physics but also in other disciplines.

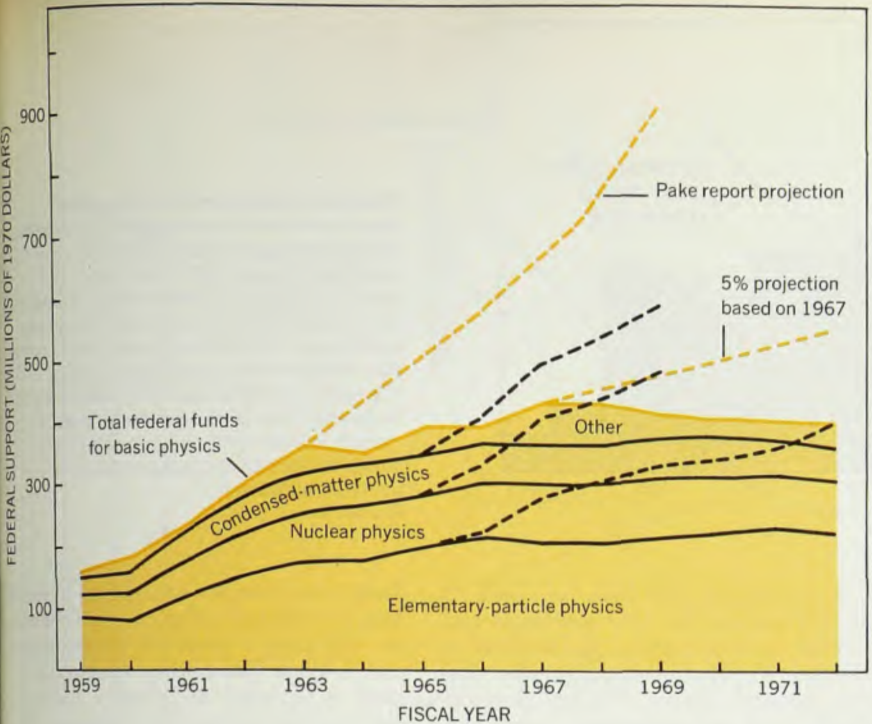
As the problems of society have multiplied—problems of population, poverty and pollution, to name only three—largely coincidentally and unhappily, an erosion of these characteristics of breadth and flexibility has occurred, with a corresponding reduction in the effectiveness of physicists as partners in the solution of societal problems. This situation led the Committee to much more intensive study of educational and manpower questions in physics than has been undertaken previously and to explicit recommendations to the scientific and academic communities for steps toward the resolution of problems in these areas.

Again in contrast to earlier surveys and in recognition of the rapidly growing importance of work at the interfaces between physics and other sciences and disciplines, we have devoted extensive effort to the achievement of a better understanding of what contribution physics might make in these interface areas and what implications such activity might, in turn, have for the structure of and activity and training in the physics enterprise. Work at the interfaces ranges from the most abstruse to the most practical. An example of the former is the astrophysicist's search for understanding of the mechanism for the total collapse of a star into inconceivably small dimensions, together with the study of its light, its magnetic fields and all other evidence of its former presence. The search for better isotopes for diagnosis and treatment of cancer, or the search for understanding of the mechanisms of nerve action, in biophysics, to alleviate ever more of the crippling afflictions that plague mankind are examples of the latter. In geophysics and planetary sciences, as a single additional example, the long-awaited understanding and prediction of major earthquakes may be at hand, with most profound practical and social consequences.

In short, in this Report the Committee has attempted not only to consider the internal logic of physics but also to put physics into a much broader context and perspective both in science and technology and in the whole of US society.

Committee and panels

The members of the Survey Committee were appointed by Frederick Seitz, president of NAS in 1969, and by his successor Philip Handler. At about the same time, a parallel committee, chaired by Jesse Greenstein, was charged with the responsibility of



Distribution of federal funds for basic physics. Although elementary-particle physics dominates here, condensed-matter physics dominates in industrial support (see the table below), and the federal–industrial totals for the two subfields are about equal.
Figure 2

surveying the opportunities and needs of astronomy. Both committees have functioned under the auspices of COSPUP, which is headed by Harvey Brooks. (See the box on page 26 for a list of members of the Physics Survey Committee.) In developing its report, the Survey Committee early decided that it needed detailed information from panels of experts in each of a number of subfields. Several of these subfields have relatively well defined and traditional boundaries in physics. In addition, there are several important interfaces between physics and other sciences. In the case of the interface with astronomy, which is a particularly active and overlapping one, the Physics and the Astronomy Survey Committees agreed to use a joint panel to report on astrophysics and relativity, an area of special interest to both. The broad overlap of physics with geology, oceanography, terrestrial and planetary atmospheric studies, and other environmental sciences was defined as earth and planetary physics, and a panel was established to survey it. In covering the physics–chemistry and physics–biology interfaces, the broader designations physics in chemistry and physics in biology were chosen to avoid restricting the study panels to the already traditional boundaries of these established interdisciplinary fields.

Although each panel, particularly those in the core subfields, was asked to consider the interaction of its subfields with technology, the Committee anticipated that the emphasis would be on recent developments that advanced the state of the art and on what is generally known as high technology. Therefore, to include also the active instrumentation interface between physics and the more traditional manufacturing sectors of the economy—steel, drugs, chemicals and consumer goods, to name only a few in which many old parameters are being measured and controlled in new and ingenious ways—a separate panel was established with the specific mission of examining the entire range of US instrumentation activities.

Two additional panels were appointed to centralize the statistical-data collection activities of the Survey and to address the questions of physics in education and education in physics. (A list of the panels and their chairmen is given in the box on page 31.) In addition, the Survey benefited enormously from assistance on a wide range of topics from a number of smaller working groups and individuals.

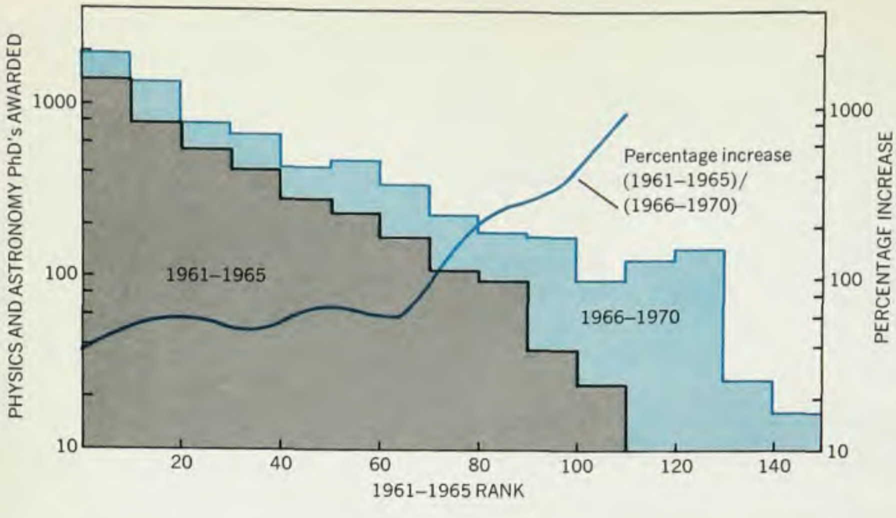
Organization of the report

The Committee report comprises 14 chapters in all. In this brief preview I can at best provide a kind of "road map"—some indication of the scope and direction of the Committee activities and a brief indication of how we arrived at some of our most important recommendations.

Chapter 2 is, in a sense, a summary of the Committee findings and is directed to three quite distinct audiences: the federal government, the scientific (and particularly the physics) community as a whole, and the educational community spanning the entire range from elementary through graduate and postdoctoral training. In chapter 3 we discuss in some depth the nature of physics as a science and as a part of Western culture. We address such basic questions as: What is the science of physics? Why are physicists interested in it? And why should anyone else be interested in it?

Operating Costs for US Basic Physics Subfields in Fiscal Year 1970 (millions of dollars)

Subfield	Federal funds	Percentage of total federal funds	Estimated industrial funds	Total federal and industrial funds	Percentage of total federal and industrial funds
Acoustics	14	3	1	15	3
Astrophysics and relativity	60	13	—	60	11
Atomic, molecular and electron	13	3	7	20	4
Condensed matter	56	12	80	136	24
Nuclear	73	16	2	75	13
Elementary particles	150	33	–	150	27
Plasmas and fluids	77	17	10	87	16
Optics	12	3	7	19	3



Changing patterns in PhD production become evident when academic institutions are ranked by the number of PhD's they awarded between 1961 and 1965. The leading institutions, responding to perceived employment difficulties for their graduates and to local financial problems, have cut the size of their entering graduate classes. The result, as these data from the National Research Council show, has not been a reduction in the entering population; the students have simply gone to the lower-ranked institutions.
Figure 3

Members of the Physics Survey Committee

D. Allan Bromley, Yale University, Chairman
*Daniel Alpert, University of Illinois
Raymond Bowers, Cornell University
Joseph W. Chamberlain, The Lunar Science Institute
Herman Feshbach, MIT
George B. Field, University of California, Berkeley
Ronald Geballe, University of Washington
Conyers Herring, Bell Telephone Laboratories, Inc
Arthur R. Kantrowitz, AVCO-Everett Research Laboratory
Thomas Lauritsen, California Institute of Technology
Franklin A. Long, Cornell University
Emanuel R. Piore, IBM
Edward M. Purcell, Harvard University
Robert G. Sachs, University of Chicago
*Charles H. Townes, University of California, Berkeley
Alvin Weinberg, Oak Ridge National Laboratory
Victor F. Weisskopf, MIT

Ex officio
Harvey Brooks, Harvard University
Edwin L. Goldwasser, National Accelerator Laboratory
H. William Koch, American Institute of Physics
Roman Smoluchowski, Princeton University

**Members of the original Survey Committee.* Other responsibilities precluded these physicists from participating in other than the early deliberations.

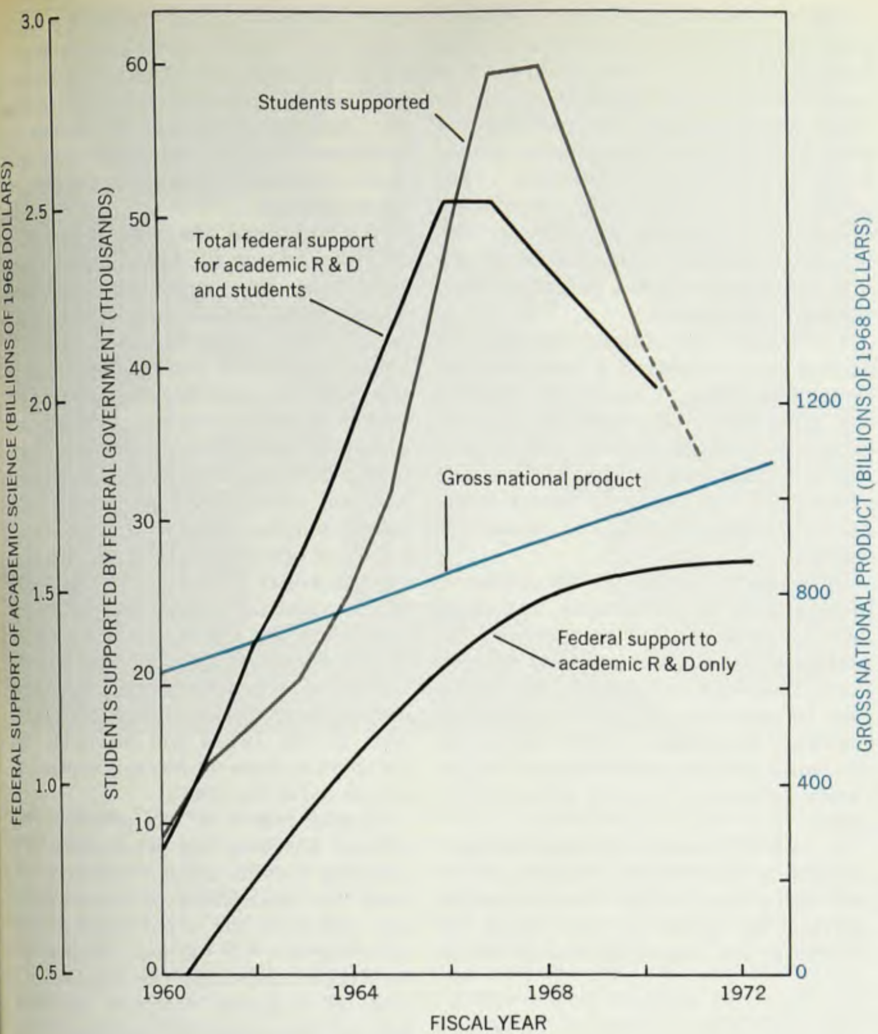
A summary for each subfield of physics and for the interface areas considered in the Survey is included in chapter 4. Each summary describes the present status, recent developments and achievements, and outstanding opportunities now identified, together with examples that demonstrate the vital unity and coherence of physics. This unity is the subject of the concluding section of the chapter, in which we illustrate first the remarkable similarity of concepts and theoretical techniques that are employed in condensed-matter, atomic and molecular, nuclear, and elementary-particle physics, and then the even more remarkable extent to which almost every branch of classical and modern physics contributes to the understanding of the recent beautiful measurements on pulsars. In considering achievements and opportunities we have focused on those relating to the solution of major national problems and to other fields of science and technology as well as those internal to physics. This chapter and the preceding one have been written with the hope of providing a convenient and concise overview of all of physics at a level of treatment that makes it accessible—and, we hope, interesting—to any interested layman and most particularly to students.

We have divided each subfield into program elements: These are scientific subgroupings having reasonably identifiable and unambiguous boundaries with which it is possible to associate certain reasonably accurate fractions of the total manpower and federal funding in each subfield. These program elements form the basis for our subsequent development of priorities and program emphases.

Chapter 5 is in many ways the heart of the report in that it attempts to address these very difficult questions of priority, program emphases and levels of support. Because new developments and discoveries can change situations and priorities in physics (as indeed in any human enterprise) in rapid and unexpected fashion, the Committee thought it desirable to emphasize and develop the criteria that could be used as a basis for priority decisions rather than the specific decisions. Exceptions, of course, occur, as in the case of major facilities.

To this end we have examined in detail many of the approaches to priority determination in science that have been discussed in recent years, and we include in chapter 5 our evaluation of the positive and negative aspects of each. From this broader examination we have evolved our own set of criteria—much modified in the course of trial application to the sets of program elements developed in chapter 4. We have found it convenient and effective to divide these criteria into three classes: intrinsic, relating to the internal logic of a science and its fundamental bases; extrinsic, relating to its potential for application in other sciences; and structural, relating to available manpower, instrumentation and institutions and to questions of opportunity and continuity.

We have refined these criteria by applying them, in a jury-rating sense, to the program elements of the core subfields of physics. In chapter 5 we also illustrate the application of the first two classes of criteria. Because the structural criteria depend to a much greater extent on detailed knowledge of the individual research project and investigator or group, we have not attempted any equivalent general illustration of their use. Instead, we have selected as illustrations certain situations in which structural considerations play a predominant role; for example, situations in which major facilities, approved and placed under construction in the mid-1960's, are now becoming operational and require a step-function increase in funds for operation. If, under declining or even level support conditions, we find it necessary to obtain these incremental funds through



Nonlinearity of the physics enterprise. In 1962 a report urged the Government to find ways to accelerate the training of scientists and engineers for the envisaged national military and space programs. The universities responded enthusiastically to the resulting increase in Government fellowships and traineeships (gray line) and in Government aid to universities and colleges for academic science (black curve), and they have had difficulty adjusting to the current phasedown in support. A principal aim of the Survey Committee report is to avoid such oscillations in the future. (Data here are from the National Science Foundation.) Figure 4

selective termination of other ongoing programs, the much greater size and costs of the new facilities would require the elimination of much of the present high-quality activity in each of the subfields concerned.

Finally, we address the difficult questions involved in any attempt to establish a national funding level for physics—or indeed for any science or other activity that depends heavily on federal funds—and evaluate these difficulties in relation to several recently proposed mechanisms.

We do not recommend an overall detailed national physics program level. This omission reflects the Committee's conclusion that it is impossible for any such group to develop, within the relatively limited time and level of activity that are possible, either adequate information or insight to make such a detailed attempt meaningful. Nor are we convinced that it is inherently desirable for any such small group to attempt to determine national priorities at this level of detail.

What we have suggested are criteria and a mechanism for their use that may enable intercomparison among subfields, or fields, of science on a more objective basis. We have elicited from the various panels detailed budgetary projections adequate to permit interpolation to match a wide range of possible funding levels and thus have attempted to provide contingency alternatives. I shall return to these.

In chapter 6 we attempt to describe the short- and long-range consequences for physics, science, the US research enterprise and the nation as a whole of continued deterioration of federal support. Beginning in 1968 with the abrupt change in the growth rate of support for physics, a wide variety of what were regarded as temporary or short-term mechanisms were developed to sustain individual research programs or groups until better days. Some of these measures had beneficial effects in forcing maximum efficiency in the use of available resources. But at the same time many of these have other effects—some of very subtle character—that in the long run can seriously weaken or destroy whole segments of the research community. Measures that are tolerable for a few years as stop-gap measures become frozen or institutionalized if too long continued—and often with very unfortunate consequences.

We do not claim any special position or consideration for physics, although for a variety of reasons that we discuss throughout the Report its problems are among the more serious in US science; we recognize that other segments of the US scientific, industrial and technological sectors have suffered major disruption also. Our discussion focuses on physics because we know it intimately. However, we believe that the observed phenomena may have much greater generality and that it is extremely important that there be greatly increased public awareness of the consequences of a continuing deterioration in the support of US science.

Physics and US society

The role of physicists and physics in US society is considered in chapter 7.

It illustrates, through the discussion of selected examples, the contributions that both have made and continue to make to society. It also highlights some problems that have developed recently in the interaction between physics and society. Here, too, we discuss the connections between physics and the health of the national economy through the channel of high-technology industries, in particular, and we also compare the research and development activities in several foreign countries with that in the US.

We argue that to remain competitive in the international marketplace US industry must not only increase the effectiveness and speed with which new scientific discoveries and developments are translated into technology and applications but also increase significantly the productivity of the individual worker. As sensitivity to problems of the environment and the unforeseen side effects of technology grows, it will be necessary to carry research farther, in parallel with technological developments, than has been traditional in the past; it will also be essential to bring imaginative new science and technology to bear on the problem areas arising from misuse of *existing* technologies.

Physicists have already demonstrated their ability to respond to such challenges of attacking old problems in new ways, of identifying entirely new problems and of applying science to practical problems in entirely new and imaginative ways. We believe that pressures for such approaches will reverse the trend of the past decade wherein physicists in industry tended to be replaced by engineers. The stakes are high, but significant changes, particularly in attitude, will be required on the part of both academia and industry if the potential benefits are to be realized.

The physics community has from its earliest days displayed a truly international character. Chapter 8 considers the implications of international interaction and cooperation for US physics and the contributions that the physics community can make to better international understanding and communication.

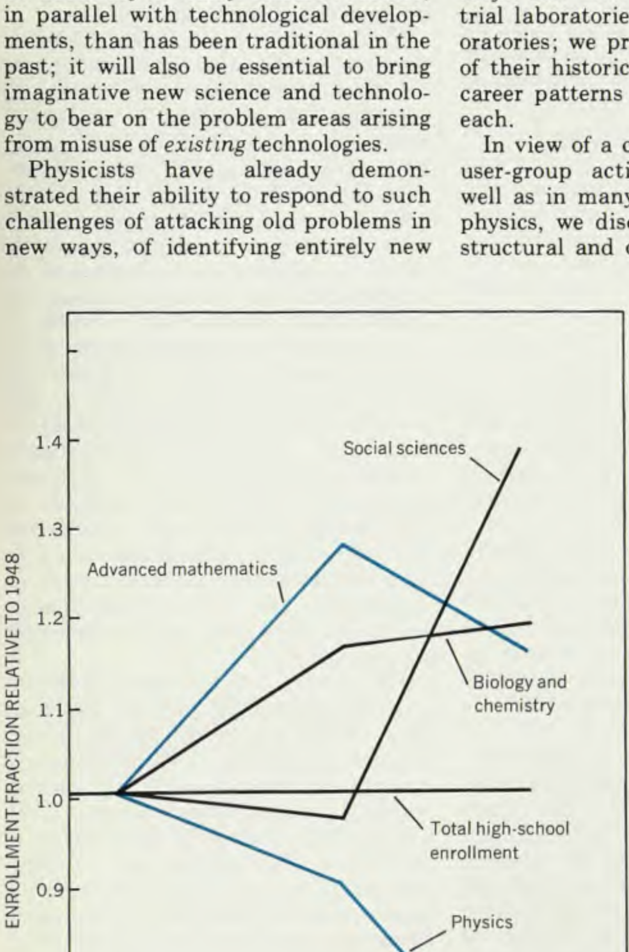
In chapter 9 we discuss the nature of physics and its institutions and show how the evolution of science has led naturally to the development of three major foci—the universities, the industrial laboratories and the national laboratories; we present a brief discussion of their historical evolution and of the career patterns of typical physicists in each.

In view of a continuing trend toward user-group activity in theoretical as well as in many kinds of experimental physics, we discuss in some detail the structural and organizational problems that can arise in such user-group situations and present some recommendations for their alleviation. We discuss, too, possible mechanisms for increasing the interaction among the various institutions and the changes in each that such increased interaction might require or imply.

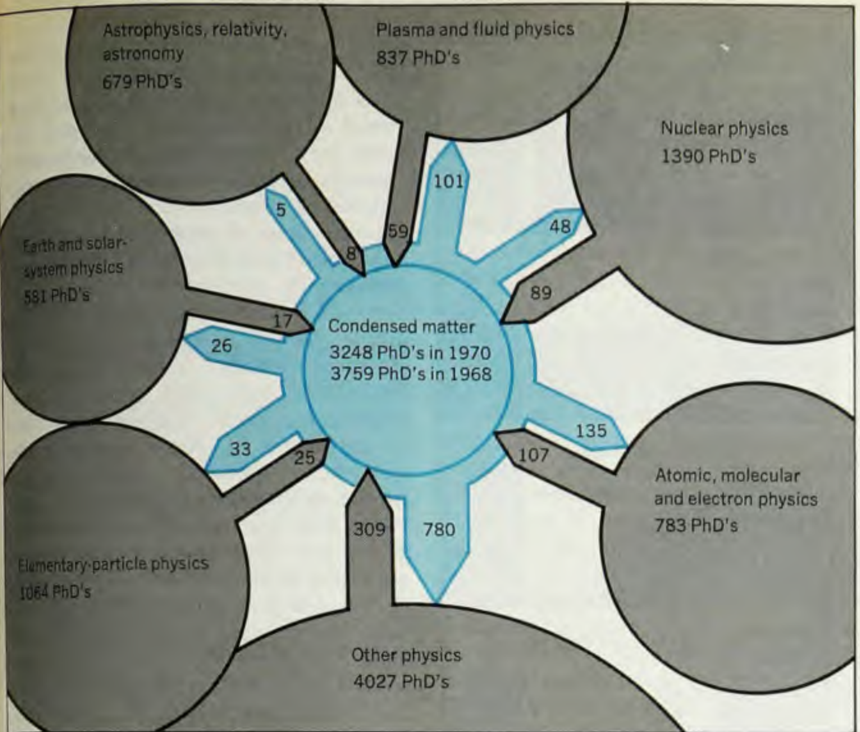
We examined the 1968 distribution of PhD and non-PhD physicists by subfield and by employing institution. These data, like so many others in our report, have been obtained from detailed mining of the master tapes of the NSF National Register of Scientific and Technical Personnel. There are about 17 000 PhD physicists, with about 25% in condensed-matter physics, and about 20 000 non-PhD's, with many working outside the traditional areas of physics. (See S. Barisch, PHYSICS TODAY, October 1971, page 40.) The industrial component, which is about 23% for PhD's and 27% for non-PhD's, is particularly important for the future of physics, because academic employment opportunities for physicists in the 1970's will inevitably fall far short of those of the rapid expansionary period of the 1960's.

Closely linked to the growth of US physics has been the development of a complex federal support structure; indeed the multiplicity of support channels has been one of the major sources of strength of US physics. Because information concerning the way that this complex support structure functions has not been readily available in the past, and because we believe that much misunderstanding and misinformation are current throughout the physics community, we have provided a brief sketch of the historical origins of the present support mechanisms and of their current operation as viewed by a prospective recipient of federal support. Finally, we briefly discuss the structure and functioning of the many federal agencies that provide funds for research in physics.

How large is the US physics enterprise? Figure 2 shows the distribution of federal funds for basic physics research; the characteristic flattening and slow decline since 1967 is clearly evident. Consideration of federal



Downward trend in high-school physics enrollments withstood even the effect of Sputnik, perhaps because some of the most effective physics teachers then left the high schools for more attractive jobs.
Figure 5



Mobility in physics is greater than is often believed. Data from the 1970 National Register of Scientific and Technical Personnel show that subfield barriers are rather permeable.
Figure 6

funding alone, however, leads to a distorted view of the total support of US physics, and we have been successful in carrying out a sampling study of industrial support of basic physics research as well. The table on page 25 includes both federal and industrial support; it is interesting to note, for example, that when both sources of support are considered, elementary-particle and condensed-matter physics enjoy roughly the same total support. Nor is this the entire story. Although there is clearly a degree of double counting, inasmuch as a significant fraction of federal support funding is devoted to payment of physicist salaries, it is of interest to obtain a measure of the nonfederal, nonindustrial support of basic physics from the total annual US expenditure on physics teaching. Making appropriate estimates for the fraction of their time devoted to physics, we find an annual expenditure from elementary through high-school teacher salaries of $310 million; college and university faculty teaching salaries total some $125 million per year.

Physics and education

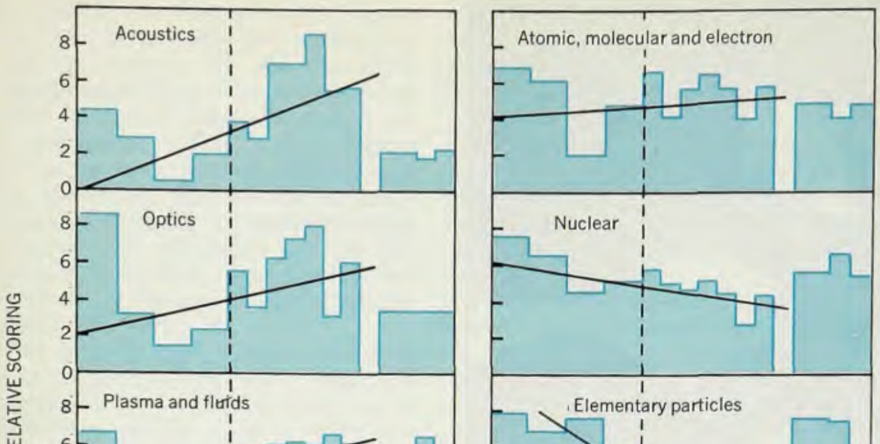
Because education is so vital to the entire physics community, and because, in turn, physics has much to contribute to education in its broadest interpretation, we have examined extensively the entire US educational enterprise as it relates to both education in physics and physics in education. This examination covers the range from elementary school to graduate and midcareer education. At all levels we found significant problems that must be considered if physics is to realize its potential contributions to US society, and we address recommendations to the institutions and agencies that we believe are best qualified to resolve these problems. We discovered in our study a wide variety of statistical information that was new and often surprising, at least to members of this Survey Committee. All this information, with discussion and recommendations, appears in chapter 11.

The fraction of the total US doctoral degrees in the natural sciences and engineering that have been awarded in physics has remained remarkably constant at 11% throughout the period from 1930 to 1970; even more remarkably, much the same fraction holds in both Canada and the UK under quite different societal conditions.

Where have these doctoral degrees been awarded? Figure 3 shows the pertinent data and highlights a disturbing trend. The indicated ranking here is purely on the basis of the number of PhD degrees awarded in physics and astronomy in the 1961–1965 period. Since 1970, the 20 or so established universities that have consistently educated some 50% of the total US doctoral graduates, in response both to perceived employment difficulties for their graduates and to local financial problems (particularly in the case of private institutions), typically reduced the sizes of their entering graduate student classes by some 40%. Yet the total entering graduate student population changed only little. In effect, those students denied access to universities with the most qualified faculties and best facilities simply went elsewhere. Such a shift in the centroid of US graduate education toward less qualified institutions can have very serious long-term consequences, and the Committee has addressed a number of specific recommendations to this problem.

Figure 4 illustrates, in rather striking fashion, one of the basic problems now facing physics education. Physics is an eminently nonlinear enterprise, with several equal time constants; when such a system receives an input impulse it rings. The figure clearly illustrates the first half cycle of such a ringing, induced by the introduction in 1962 (following the Gilliland report findings) of federal programs to accelerate the training of scientists and engineers needed for the envisaged national military and space programs. Responding enthusiastically to the opportunities and challenges involved in such a national program, universities expanded their facilities and faculties and by 1968 had achieved the goals initially established for 1970. Not surprisingly the federal programs were then phased down, but the universities found it extremely difficult to follow. One of the Committee's overriding functions has been to develop recommendations aimed at damping this oscillation.

There are many inputs to such recommendations. Figure 5 shows the changing patterns of high-school program choices since 1948. Even Sputnik did not reverse the downward trend in physics. Indeed it may well be that the further drop in the 1960's reflects the removal of some of the rare highly qualified and highly effective high-



Criteria for program emphases

Three sets of criteria, which emerged from discussion, were refined through application to program elements in the various subfields:

Intrinsic merit

1 To what extent is the field ripe for exploration?
2 To what extent does the field address itself to truly significant scientific questions that, if answered, offer substantial promise of opening new areas of science and new scientific questions for investigation?
3a To what extent does the field have the potential of discovering new fundamental laws of nature or of major extension of the range of validity of known laws?
3b To what extent does the field have the potential of discovering or developing broad generalizations of a fundamental nature that can provide a solid foundation for attack on broad areas of science?
4 To what extent does the field attract the most able members of the physics community at both professional and student levels?

Extrinsic merit

5 To what extent does the field contribute to progress in other scientific disciplines through transfer of its concepts or instrumentation?
6 To what extent does the field, by drawing upon adjacent areas of science for concepts, technologies and approaches, provide a stimulus for their enrichment?
7 To what extent does the field contribute to the development of technology?
8 To what extent does the field contribute to engineering, medicine or applied science and to the training of professionals in these fields?
9 To what extent does the field contribute directly to the solution of major societal problems and to the realization of societal goals?
10 To what extent does the field have immediate applications?
11 To what extent does the field contribute to national defense?
12 To what extent does activity in the field contribute to national prestige and to international cooperation?
13 To what extent does activity in the field have a direct impact upon broad public education objectives?

Structure

14a To what extent is major new instrumentation required for progress in the field?
14b To what extent is support of the field, beyond the current level, urgently required to maintain viability or to obtain a proper scientific return on major capital investments?
15 To what extent have the resources in the field been utilized effectively?
16 To what extent is the skilled and dedicated manpower necessary for the proposed programs available in the field?
17 To what extent is there a balance between the present and envisaged demand for persons trained in the field and the current rate of production of such manpower?
18 To what extent is maintenance of the field essential to the continued health of the scientific discipline in which it is embedded?

Averaged rating histogram shows scoring of the eight core subfields of physics in terms of the intrinsic and extrinsic criteria. Questions 4, 11 and 13, which are of a somewhat different character, are presented separately.
Figure 7

school physics teachers as more attractive employment opportunities developed elsewhere. We hope that the reversal of this trend in the past few years may reverse the decrease pattern; there is already fragmentary evidence for such an effect.

Some help in predicting manpower availability can be gained by following, statistically, the history of a typical cohort of US physicists. We find, for example, 460 000 twelfth-graders (124 000 of them female) taking physics in 1963–1964, only 7300 undergraduate physics majors in 1966–1967 and 5500 BS physicists in 1968. Because of the enormous attrition between the twelfth-grade physics enrollments and the junior undergraduate year, it appears clear that unless further drastic reduction in the high-school population occurs, the pool from which undergraduate physics majors are drawn will remain adequately large. Of much greater immediate concern is the dramatic decrease, beginning in 1967, in the percentage of the physics baccalaureates going on to graduate work: For about two decades, roughly 53% went on to graduate work; this had dropped rather precipitously to about 37% by 1970.

On the basis of fairly stable patterns in the past we expect a production of 1500 PhD's in physics for 1974, with very similar figures holding for 1975. If we take a more pessimistic view at each stage, we obtain 600 PhD's in 1975 and extrapolate to a marked undersupply of physicists in the late 1970's, although in all our models we face a temporary oversupply situation during the next few years. The Committee has a number of specific major recommendations to alleviate the short-range manpower problems and to maintain an adequate supply of trained physicists for the nation's needs. In particular it will be important to monitor that the annual baccalaureate production not fall below roughly 5000.

There is striking evidence in these data of the rather fantastic filter that operates against women physicists in the US in the transition from high school to college. In the question of women and of minority-group physicists, the educational enterprise is woefully inadequate.

A final important aspect of education, broadly interpreted, is public awareness of science and of its possible contributions to a better life. In the US, efforts to inform and educate the public about science are few and usually of poor quality. The scientific community must accept a large share of the responsibility for this situation. If the present antiscience trend is to be reversed, individual scientists and scientific organizations must be prepared

Panels and chairmen

Acoustics
Robert T. Beyer, Brown University
Astrophysics and relativity (joint panel with the Astronomy Survey)
George B. Field, University of California, Berkeley
Atomic, molecular and electron physics
Nicolaas Bloembergen, Harvard University
Earth and planetary physics
Richard M. Goody, Harvard University
Education
Ronald Geballe, University of Washington
Elementary-particle physics
Robert G. Sachs, University of Chicago
Instrumentation
Nathan Cohn, Leeds and Northrup Co
Nuclear physics
Joseph Weneser, Brookhaven National Laboratory
Optics
W. Lewis Hyde, New York University
Physics of condensed matter
George H. Vineyard, Brookhaven National Laboratory
Physics in biology
Robert Shulman, Bell Telephone Laboratories
Physics in chemistry
R. Stephen Berry
Plasma physics and the physics of fluids
Stirling A. Colgate, New Mexico Institute of Mining & Technology
Statistical Data
Conyers Herring, Bell Telephone Laboratories

to spend more of their time and money than has been the case previously in fulfilling their obligation to inform a much larger segment of the US public. Several of the Committee recommendations are directed to this end.

Using the extensive information that we have extracted from the National Register data tapes as well as input from our own questionnaires and those of the Manpower Committees of APS and AIP, we have assembled what we believe to be the most complete information concerning the training and use of US physicists yet available. We include data on mobility, sociological aspects of physics and a brief historical study, and we project physics manpower needs with several different models. Although serious problems clearly exist in regard to employment opportunities in the traditional types of jobs that physicists have held, there is also evidence, as we have noted, to suggest that the scientific and academic communities are in some cases overreacting, and that unless some action is taken the oscillatory phenomena associated with the supply of US physicists in the recent past will not be adequately damped. What emerges clearly from these studies is that the growth in tenured academic employment opportunities during the 1960's was indeed anomalous and that it is essential to take steps to broaden the motivations and interests of young US physicists beyond the academic sector—as was typical before the late 1950's, for example—or serious dissatisfaction and alienation will remain. We discuss these considerations in chapter 12.

Figure 6 is typical of the migration data that we have extracted from the National Register tapes for each physics subfield considered in the Survey. Contrary to much traditional wisdom, we find that physicists are mobile and that subfield barriers are quite permeable. Indeed we find that well over one-third of all US physicists have changed subfields during the past decade.

Information of physics

Unfortunately, the available mechanisms for disseminating and consolidating the information of physics, so that it is readily and conveniently available to all potential users, have simply failed to keep pace in many areas with the rapidly increasing rate at which individual facts can be wrested from nature in modern research laboratories. In chapter 13 we describe in detail the functioning of the various media for the communication of the information of physics. Again, we have developed an extensive body of new statistical information. We discuss these data in relation to current problems and develop specific recommendations directed toward different sectors of the physics enterprise.

We have found that traditional wisdom here too is frequently without foundation in fact. To do so we have carried out several informal operations-research studies. These have included extensive anecdotal studies with working physicists to trace the sources of their ideas and new developments, and sampling studies to discover the age distribution of journals most used in large industrial, national-laboratory and university research libraries. Other sampling studies were designed to evolve an objective measure of the quality of randomly selected publications. In these, papers were submitted to panels of experts for grading; the lowest grade was achieved by papers that demonstrably set back their entire field of physics and the highest by papers that made major and lasting contributions. Several rather surprising conclusions emerged from these studies:

- Primary journals are the most important single source of physics communication, with informal oral communication a close second.
- The obsolescence halflife of primary-journal articles is about eight years.
- Most of the primary literature of physics is apparently useful and used. A sample study in condensed-matter physics shows that 33% of the papers made additions of conceptual interest and lasting value; only 8% of the papers were judged as worthless by any member of the evaluation panel.
- Any mechanism that would result in a saving of λ% of the total time the average physicist devotes to communication in physics would be worth roughly (λ/100) times ($300–$600) million per year in the US.

Priorities and program emphases

During the 1950's and early 1960's, US science, reflecting generous public support, enjoyed a period of unprecedented growth in both quality and scope. In this period almost every competent scientist and almost every good idea could find support without undue delay. Annual growth rates of between 15 and 25% were not uncommon. The results were new knowledge, new technologies and a large body of trained manpower commensurate with this national investment.

Such a growth rate could not continue indefinitely, and indeed, in the period since 1967 the support of many areas of US science has seen marked leveling or effective decline—this is particularly true of physics. When science funding is increasing, as in the past two decades, questions of priority receive little overt attention, because worthy new projects and new investigators can be supported with little detriment to work already under way. With ample funding for new initiatives and the capacity to exploit new opportunities, it is relatively easy to maintain the vitality of the scientific enterprise; it is much more difficult to do so under conditions in which not all good ideas can find timely support and where many competent scientists cannot find professional opportunities that exploit even a part of their training. The nation is then in a position of being less able to gamble, and the cost of wrong choices becomes much higher.

Questions of priority, although often not made explicit, are an integral part of all human endeavor. Science is no exception. Scientists, science advisors, managers of science and the scientific community must decide in one area or another what to do next and where to devote energies and resources. What areas of science are most worth pursuing? Which are most deserving of encouragement and support? These are difficult questions to which there are neither obvious answers nor, indeed, obvious methodologies for obtaining answers.

As in many other human affairs, a multiplicity of criteria must be brought to bear. Thus, perhaps, the best way to approach the question of priorities in science is to try to identify and develop the criteria by which they are made. There is now an extensive literature in this area; as a Committee we have studied this earlier work and have devoted much effort to the evolution of a set of criteria that we have found particularly useful in appraising the needs and potentials of the different subfields of physics (see figure 7). A number of approaches that have been proposed for the establishment of priorities are considered in the survey report together with what we as a Committee consider to be their positive and negative aspects.

After much discussion of the various possibilities, the Committee decided upon an approach that combines many of their features: a "jury rating" of Committee members as to the appropriate emphasis that should be applied to a given activity within the next five years, taking account of both the internal, intellectual needs of physics and their assessment of the impact of these scientific developments on other sciences, on technology and on societal problems generally. It must be emphasized that any such rating system has a value that is relatively short-lived, because science changes so rapidly. Moreover, any group of people as small as the Physics Survey Committee is bound to represent certain prejudices or special interests that would be different for a differently selected but equally competent group of comparable size. The numbers are too small for nonobjective biases to be mutually cancelling.

The goal has been to identify those program elements in physics that, on the basis of our criteria, should experience large *relative* growth rates. The questions of *overall* growth rates and support levels for physics and the development of contingency alternatives designed to respond most effectively to different levels of such total support are taken up below.

To illuminate the criteria through trial application to actual cases (and it should be noted that this process resulted in extensive modification of the Committee's initial criteria) and to discover the degree of consensus that existed within the Committee, matrices were prepared bearing the program elements of each subfield (see chapter 4) as rows and the criteria as columns. (This procedure was not applied to the interface fields such as chemical physics, biophysics and earth and space physics, which present special problems and were not considered amenable to this approach. In large measure this reflects the fact that the physics components of these interface areas, although very important, are not dominant. Lacking a more comprehensive survey of these fields to place their physics elements in better perspective, we have not considered ourselves competent to carry out a similar jury rating.)

The structural criteria were not included in this exercise because, to a much greater extent than those of an intrinsic and extrinsic character, the structural questions are of a detailed nature, applicable to each specific project, and they change rapidly with time. In arriving at ultimate program emphasis decisions, these structural criteria must be given due weight, but to apply them effectively a detailed study of the individual program elements, and of the individual research projects in them, is required. Certain exceptional cases for which the structure criteria have a direct bearing on our recommendations are discussed below.

With the reports of subfield panels in hand, and following a brief presentation of the program elements by an advocate drawn from the Committee membership, the matrix elements were rated on a 0–10 scale by each Committee member. These ratings were subsequently combined to obtain the averaged matrices for each subfield.

Figure 7 is the averaged rating histogram plotted in this fashion for the above-mentioned eight internal subfields of physics. Inasmuch as questions 4, 11 and 13 are of a somewhat different character than the remaining ones, they are presented in a separate histogram to the right of each figure. (Histograms of the Survey Committee's average jury rating of the individual program elements in each subfield appear in our report.)

Several interesting checks that give a character signature for each subfield emerge immediately from inspection of this figure. Not unexpectedly, acoustics and optics have a signature that strongly emphasizes the extrinsic criteria, whereas astrophysics and relativity and elementary-particle physics emphasize the intrinsic criteria. The remaining subfields fall between these extremes in ordering, a result entirely consistent with the intuition of the Committee members.

Most important was that, despite widely different backgrounds and interests, the spread in the ratings of the Committee members on individual matrix elements was small. In part this is a reflection of the fact that the relatively large number of criteria that the Committee chose to use makes for a more objective evaluation of each individual criterion.

Overall scoring of program elements

1. Lasers and masers
2. National Accelerator Laboratory
3. Quantum optics
4. University groups-EPP
5. Stanford Linear Accelerator
6. Nuclear dynamics
7. Major facilities-EPP, AGS Improvement
8. Brookhaven AGS
9. Nuclear excitations
10. Heavy-ion interactions
11. Higher-energy nuclear physics
12. Nuclear astrophysics
13. Theoretical relativistic astrophysics
14. Neutron physics
15. Nuclear theory
16. Very large radio arrays
17. X- and gamma-ray observatory
18. Turbulence in fluid dynamics
19. Superfluidity
20. Infrared astronomy
21. General-relativity tests
22. Oceanography
23. Atomic and molecular beams
24. Laser-related light sources
25. Controlled fusion

The order here within any group of, say, five program elements is not significant. Elements in color are those considered to be high-leverage programs. Other high-leverage program elements are (in arbitrary order of decreasing numbers of PhD physicists in the corresponding subfield) macroscopic quantum phenomena, scattering studies in solids and liquids, biophysical acoustics and nonlinear optics.

The box on this page shows the first 25 of the 69 program elements considered by the Committee listed according to overall scoring. We emphasize that *within any restricted area of the listing the relative ordering should not be considered significant.*

The approach adopted herein and the criteria evolved may have rather general utility in providing a somewhat more coherent and objective evaluation of program emphases than the more subjective intuition and folklore that has tended to characterize previous attempts of the scientific community.

Thus far, consideration has been given to the distribution of a total level of funding, allocated to the national physics enterprise, among the subfields of physics without explicit consideration of what the total level might be. It is abundantly clear, however, that the distribution is inevitably a strong function of this total level.

Among the most discussed mechanisms for the establishment of long-term support levels for science have been:

- Tie the support of science to the Gross National Product (GNP).
- Because the scientific community was in a state of robust health in 1967, tie projected support levels from that point to the GNP; this leaves an obvious present deficit that would be rectified by step funding increments in the short-range future.
- Because a healthy US scientific enterprise is of particular importance to the well being of our high-technology industries and these in turn to the national economic health, tie projected supported levels to the productivity of the high-technology sector of the national economy.

We examine each of these at some length and conclude that none will suffice. The problems are compounded by the fact that, in practice, funding finally made available to the subfields of physics is not interchangeable. Lack of recognition of this situation has already led to tensions within the physics community and even within subfields of physics.

Contingency alternatives

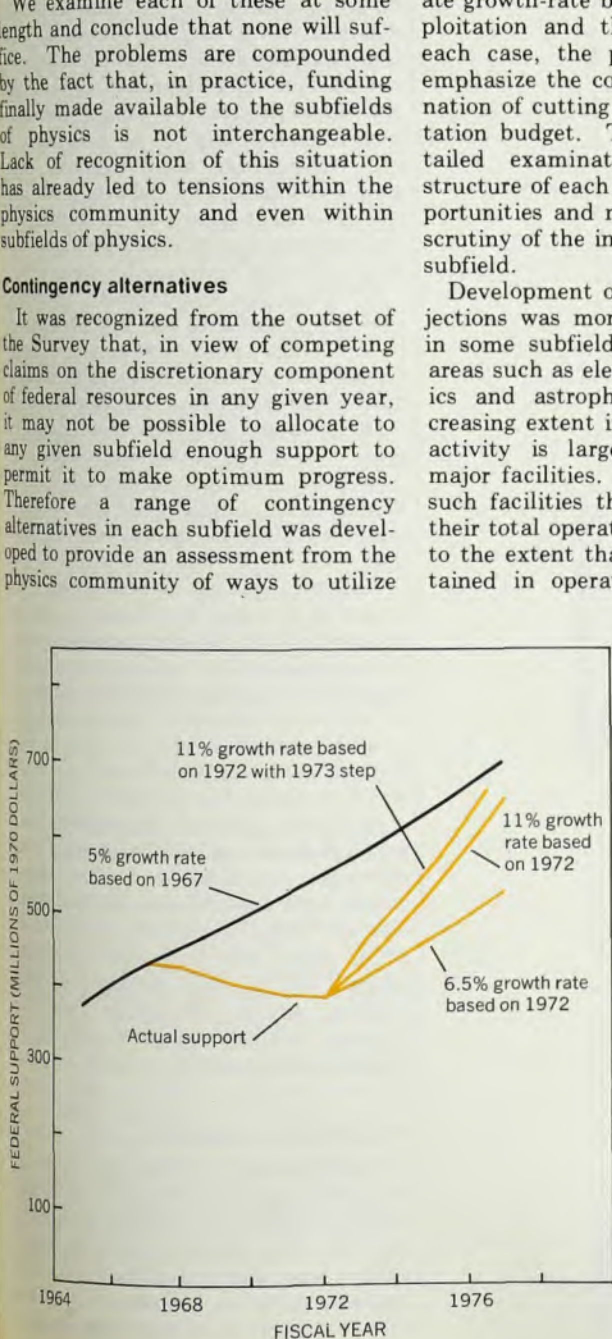
It was recognized from the outset of the Survey that, in view of competing claims on the discretionary component of federal resources in any given year, it may not be possible to allocate to any given subfield enough support to permit it to make optimum progress. Therefore a range of contingency alternatives in each subfield was developed to provide an assessment from the physics community of ways to utilize most effectively whatever funding support becomes available—most effectively from the viewpoint of the overall health of physics and of the contribution that physics can make to US society.

Accordingly, the initial charge to subfield panels requested that they develop, in as much detail as possible, programs for their subfields under various assumed funding projections: a so-called exploitation budget that attempts to exploit all the opportunities, both intrinsic and extrinsic, now perceived; a level budget—level in dollars of constant buying power; and a declining budget—declining at an arbitrarily established rate of between 6 and 7.5% per year. To obtain the hoped-for interpolation possibilities, it was necessary to evolve an intermediate growth-rate budget between the exploitation and the level budgets. In each case, the panels were asked to emphasize the costs to science and the nation of cutting back from the exploitation budget. This required very detailed examination of the internal structure of each subfield and of its opportunities and needs as well as sharp scrutiny of the internal priorities of the subfield.

Development of such budgetary projections was more easily accomplished in some subfields than in others. In areas such as elementary-particle physics and astrophysics—and to an increasing extent in nuclear physics—the activity is largely quantized around major facilities. It is characteristic of such facilities that a large fraction of their total operating costs are invariant to the extent that the facility is maintained in operational status; support and development staffs, power for magnets, radiofrequency sources and other systems must all be provided unless the facility is closed down. This is reflected in a very large leverage factor; that is, very small percentage changes in the overall operating budgets can be reflected as major fractions of the discretionary component of these budgets—that fraction that goes directly to the pursuit of research and not simply to keeping the doors open.

In such heavily quantized subfields, reductions below the exploitation budget typically have involved the closing down of entire facilities or, at least, major change in the style and scope of operation permitted. This results in a corresponding reduction of the manpower that the subfield can accommodate, quite apart from possible opportunities for new personnel now being trained. The dislocation and career disruptions involved here for excellent scientists and support personnel is a waste of resources, which in our opinion the nation can ill afford.

In less quantized subfields such as condensed-matter and atomic, molecular and electron physics the effects of budgetary reductions are less obvious and the manpower problems less extreme. Because the research is much less facility-intensive, reduced funding means that the objectives of each scientist or scientific group are lowered—less work is done, fewer challenges are met, and the field slows down. Although this can proceed for a time without overt symptoms of serious trouble, trouble is there; morale drops, enthusiasm dwindles, and the subfield is less able to respond to challenges or opportunities. Quite apart from these



Contingency alternatives. An eleven percent annual increase, with a 1973 step-function increment, would allow exploitation of the opportunities in each subfield. Even this growth rate, however, would not bring the field to the level it would have reached had it followed a steady five percent growth rate since 1967 (black line).
Figure 8

differences, however, all subfields have concluded that a budgetary level declining at 7.5% per year would, within five years, bring the subfield below that critical point where productivity, however measured, falls dramatically.

Figure 8 shows the Committee synthesis of all the panel inputs. As discussed in detail in the report, a number of major facilities, including the Los Alamos Meson Physics Facility and the National Accelerator Laboratory, are scheduled for initial research utilization in fiscal year 1973, following initial approval in the mid-1960's and a lengthy construction period. To enable this turn-on without gross interference with the remaining programs in these fields, the Committee has recommended incremental step funding in 1973 (in this figure; in fact much of the required incremental funding did not become available in 1973 and must be deferred until 1974). Beyond this there existed a rather remarkable consensus that an 11% growth rate would permit exploitation of the opportunities in each subfield. As indicated in this figure, even such a growth rate would not bring the field, by 1977, to the level that it would have reached had a steady five percent annual growth rate in funding been possible since 1967.

It must be emphasized, however, that the Committee has not attempted to detail any specific national program for physics in the next five-year period in the range between the exploitation (11% growth) and flat (zero percent growth) levels of investments—both in dollars of constant purchasing power. Within each subfield, to the extent possible, this detailing has been carried out.

The fact that we do not recommend a detailed national physics program appropriate to different possible levels of funding does not reflect any unwillingness to face the difficulties inherent in any such attempt. It is unrealistic to look upon the total funding of US physics as an effective reservoir from which funding for individual program elements is parceled out without having cognizance of all the internal and external pressures and constraints within both the different funding agencies and the physics community itself. An *a priori* allocation system, which parcels out a fixed amount of total funding among predefined fields of science, is likely to be stultifying of initiative and novelty.

High-leverage situations

Small changes in funding—either up or down—can sometimes be reflected in large changes in scientific productivity. In the case of major facilities, such a large fraction of the total funding is required to keep them in operation that even small fractional changes in funding are reflected as very large changes in the research component, to which scientific productivity is much more directly coupled. In fields where new breakthroughs, either in concepts or in instrumentation, have occurred, new frontiers are opened, and investment in research at those frontiers can be expected to yield high scientific return. In other fields, again because of breakthroughs in instrumentation or ideas or because the field itself in its internal development has reached a state where further investment can be expected to yield returns of high societal importance, the leverage is high.

The relative weighting or importance assigned to each type of leverage will vary from field to field and from one support agency to another. This is healthy and proper. In examining program elements as candidates for high-leverage consideration, structural criteria play an important role. It is here, for example, that continuity considerations enter explicitly.

As illustrations of various types of high-leverage situations and the utilization of our Committee-ordered listings, in combination with the subfield panel reports, the Committee selected from the subfields 15 program elements with growth potentials that warrant high priority for their support in the next five years; these are presented in the box on page 32.

We emphasize that the increased support recommended for these program elements should not be at the expense of other activities in the subfields, although clearly some readjustment is not only necessary but also healthy as the various program elements attain different levels of scientific maturity. At the same time, it should clearly be recognized that, should only the selected program elements be supported, the overall physics research program would be totally unbalanced.

* * *

This article is adapted from a talk given at the Washington APS meeting in April. The Physics Survey was carried out under the aegis of the National Academy of Sciences Committee on Science and Public Policy with support from the Atomic Energy Commission, the Department of Defense, the National Aeronautics and Space Administration, the National Science Foundation, the American Physical Society, and the American Institute of Physics. The Committee could not have functioned without the generous assistance of a great many physicists and government program officers and owes all of them its sincere gratitude. The author should also like to take this opportunity to express his personal thanks to the members of the Survey Committee, to George Wood, Charles Reed, Bertita Compton, Beatrice Bretzfield and Mary Anne Thomson for much help and support during the entire course of the Survey. □