uses cannot be scaled up to energies higher than the SSC because of the cost. Electron-positron linear colliders are, therefore, the leading candidate for future accelerator design.

Much of the technology for the electron-positron linear collider is as yet undeveloped. With the understanding that preliminary estimates are therefore surrounded by a high degree of uncertainty, the calculations suggest that an electron-positron linear collider would cost roughly $1 billion to $2 billion.

The principal scientific benefit of building an electron-positron linear collider with a mass reach approaching 1 trillion electron volts is that it would reach new energy levels for a lower total cost than the SSC, thus freeing up funds for other science, including other high-energy physics. Compared with joining the LHC, it would increase the number of instruments available to perform high-energy physics experiments and ensure that the high-energy physics community in the United States had a machine at the forefront of high-energy research. Such machines, however, will rely on developments in technology that may not occur. Electron-positron linear colliders carry the risk of never being able to reach these high energy levels economically, although they stand a good chance of reaching levels that are high by current standards. Furthermore, the recently commissioned Stanford Linear Collider, which is intended to test the new electron-positron linear collider technology, has been temporarily shut down because of technical problems, although many of those problems stem from recycled equipment from an older accelerator.

CHAPTER I

INTRODUCTION

Since 1945, the federal government has supported high-energy physics generously and funded the construction of ever larger particle accelerators. These scientific instruments have deepened the understanding of particle physics and produced a theory--the so-called "standard model"--that now dominates physicists' view of the world.[1] Extending the standard model's theories now requires substantially more powerful instruments than currently exist.

The latest accelerator proposed for construction in this series is the Superconducting Super Collider (SSC). The SSC is larger, more sophisticated, and more expensive than any accelerator yet built. It is designed to have two racetrack-shaped rings, each composed of a vacuum chamber surrounded by approximately 5,000 superconducting magnets and containing a proton beam with an energy of 20 trillion electron volts.[2] The most powerful facility currently in operation in the United States at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, has an energy of 0.9 trillion electron volts per beam.

The Congress has funded research and development (R&D) on various aspects of the SSC, most notably the superconducting magnets, since 1984. R&D costs for the SSC have thus far totaled $205 million, including funds appropriated for 1989 (all years are fiscal, unless otherwise noted). The Department of Energy (DOE), which funds most of U.S. high-energy physics and is in charge of the SSC, estimates that building the SSC will cost over $5.3 billion in current dollars (the constant dollar estimate is $4.4 billion in fiscal year 1988 dollars). This report analyzes the benefits, costs, and risks of con-

1. This report uses particle physics and high-energy physics interchangeably when referring to contemporary events. Particle physics is an older field of study; its high-energy phase began relatively recently.

2. One electron volt is the energy gained by an electron when accelerated by one volt. See the glossary at the end of this report for definitions.

structing the SSC and presents some of the options that the Congress might consider.

WHAT IS THE SUPERCONDUCTING SUPER COLLIDER?

The standard model for particle physics has been refined to describe two sets of fundamental particles--quarks and leptons--that are the "basic" building blocks of all matter.[3] (According to the model, neutrons and protons are made up of quarks, while the electron itself is one type of lepton.) Physicists also believe that the four fundamental forces of nature (electromagnetism, gravity, the strong force holding atomic nuclei and their components together, and the weak force governing radioactive decay) were unified at the creation of the universe when energy levels were higher. In this manner, the standard model is consistent with the "big bang" theory of cosmology.

Despite its many successes in explaining the behavior of subatomic particles, the standard model cannot be complete since it involves many arbitrary assumptions, including parameters whose numerical value cannot be explained within the model. By exploring higher energy levels, physicists hope to begin to expand the model to discover explanations for these parameters. As a first step, the SSC, if successful, would expand the current theory that explains the unity of the electromagnetic and weak forces. (Similarly, Maxwell's equations, together with Faraday's experiments, in the 19th century showed that electricity and magnetism were actually different expressions of the same force--electromagnetism.) The theory unifying these two forces is one of the notable successes of the standard model. In order to accomplish this unification, physicists have assumed the existence of a particle, often called a Higgs Boson, that provides for certain theoretical needs.[4] The Higgs Boson has never been observed, although other particles predicted by that unification theory were discovered by researchers at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland, in 1983. Scientists postu-

3. For a description of these particles and how they fit into the standard model, see Leon Lederman, "To Understand the Universe," *Issues in Science and Technology*, vol. 1, no. 4 (Summer 1985), pp. 58-61.

4. Marintus J. G. Veltman, "The Higgs Boson," *Scientific American* (November 1986), pp. 76-84.

late that it can be found only by using energy levels beyond those achievable by the current generation of accelerators. A major task of the SSC is to confirm the existence of the Higgs Boson.[5] In addition, researchers hope to discover other new particles--for example, new types of quarks--and generally investigate phenomena assumed to exist at this higher energy level.

The process of uniting the forces is also of great interest to cosmologists (scientists who study the origin, structure, and space-time relationships of the universe), since the unification of forces provides insight into the very beginnings and eventual end of the universe. Current accelerators can explain phenomena that occurred within 10^{-10} seconds after the big bang. The SSC would carry that knowledge further back to 10^{-13} seconds.[6]

The SSC in Operation

A small linear accelerator in the SSC will produce protons that will be sent through three accelerator rings--the low-energy booster, the middle-energy booster, and the high-energy booster--that will increase the energy of the protons in three steps. After they have been brought up to sufficient energy, the protons will be injected into the two main rings of superconducting magnets. There, the beams of protons will receive their final acceleration and the superconducting magnets will steer them into collision paths. After a day or more, the number of uncollided protons will drop to too low a level, and the main rings will need to be reloaded.

At the heart of the SSC, therefore, are the two beams of protons. The proton beams will be circling in opposite directions in two separate rings, which will be mounted directly on top of each other in an underground tunnel. The rings are designed to intersect at first in four, and eventually in six, chambers called interaction regions. When the proton beams intersect, some protons from each beam will

5. SSC Central Design Group, *Conceptual Design of the Superconducting Super Collider* (Berkeley, Calif.: SSC CDG, 1986), pp. 34-36.

6. "Superconducting Super Collider," *Supercurrents* (March 1988), pp. 12-16. See also David Schramm and Gary Steigman, "Particle Accelerators Test Cosmological Theory," *Scientific American* (June 1988), pp. 66-72.

collide with some protons from the other beam. (By having two moving objects collide, physicists are able to increase the energy capability of particle accelerators. A conventional analogy would be the difference between two cars colliding head on on the freeway versus one car running into a parked car.) The collisions of the protons will cause their constituent particles to interact. Specialized detectors will measure the energy and trajectory of these interactions and then store this information in computers for later analysis. The patterns of particle movement and energy that physicists find on subsequent examination will indicate whether or not they have found evidence of the particles they seek.

The physical parameters of the SSC are determined by the need to contain and direct the two high-energy proton beams. The rings of the SSC, at 53 miles in circumference, will be three times the size of the next largest accelerator (currently under construction in Europe) and more than 10 times the size of the biggest existing U.S. accelerator (the Tevatron at Fermilab). Energy containment means that the magnets that operate the SSC have to be very powerful. Conventional magnets are not strong enough--with conventional magnets, the SSC would have to be much larger. Therefore, the SSC Central Design Group, which is composed of high-energy physicists under contract to DOE, turned to superconducting magnets. (These magnets have the added advantage of reducing electricity costs, since they have no resistance to electrical current.)

The collider rings themselves are composed largely of the superconducting magnets resting inside cryostats--thermoses of liquid helium--that keep them very cold. The main rings are designed around nearly 7,700 dipole magnets, which keep the proton beams on course, and nearly 1,800 quadrupole magnets, which focus the proton beams. The dipoles, each 17 meters long, are longer than most accelerator superconducting magnets previously built. The quadrupoles, on the other hand, are comparable to the magnets in Fermilab's Tevatron, roughly 4 meters long. Most of the preconstruction research has concentrated on the dipole magnets.

CURRENT STATUS OF THE SSC

To date, the Congress has funded $205 million of SSC costs, including the next stage of SSC research, while withholding authorization for actual construction. At the same time, DOE is still trying to choose the best location for the SSC.

The Cost of the SSC

DOE currently projects that the SSC will cost $5.3 billion in current dollars. (This estimate was made before Congressional budget appropriations were completed for fiscal year 1989. Since the Congress did not grant the administration's request, total project costs will be different from this estimate.) Actual construction is to be spread over eight years. In 1988 dollars, the DOE cost estimate is $4.4 billion dollars. Construction of the accelerator itself--roughly $3.2 billion (including the superconducting magnet system projected to cost more than $1.0 billion)--accounts for almost three-quarters of these total project costs. The detectors will add another $719 million, and research and pre-operating costs account for another $440 million. Despite the inclusion of over $550 million in contingency costs in the construction estimate, the ultimate price may be higher. (The SSC costs and their associated budgetary risks are discussed in Chapter III.) In addition to construction costs, DOE estimates that the SSC will cost $270 million per year to operate.

Current Funding

The Congress has appropriated $100 million for 1989 for the SSC: $84 million for R&D, operating costs, and preliminary engineering and design, and $16 million for capital equipment related to research. This appropriation is an increase from the 1988 level of $25 million, but less than the $363 million requested by the President. The increased appropriations will allow DOE to undertake the next phase of research on the magnets, but the Congress has not approved any funds for construction.[7]

7. *Energy and Water Development Appropriation Bill, 1989*, Report No. 100-381, Senate Committee on Appropriations, to accompany H.R. 4567, 100:2 (1988), pp. 133 and 134.

Location

The location of the SSC has yet to be decided. There are currently seven finalist sites, each in a different state: Arizona, Colorado, Illinois, Michigan, North Carolina, Tennessee, and Texas. The National Academy of Sciences recommended these sites to the Secretary of Energy out of 43 sites initially submitted for consideration.[8] Currently, DOE is conducting an environmental evaluation. The Secretary of Energy is expected to make his recommendation to the President in November or December of 1988, but the final decision could be left to the next administration.

EVALUATING THE SSC

The next Congress will be confronted with the decision of whether or not to build the SSC. The SSC, like all science projects, is a risky investment: it may produce many discoveries and technology spinoffs or it may produce few such benefits in proportion to its cost. Furthermore, no quantitative measure of its output in terms of knowledge is possible. Consequently, there is no simple measure of the SSC's social rate of return--the usual economic standard for measuring the benefits of a public investment. As a result, policymakers must make a qualitative judgment about the potential risks and benefits associated with building the SSC.

8. National Academy of Sciences, *Siting the Superconducting Super Collider* (Washington, D.C.: National Academy Press, 1988). New York had been on the list of finalist states, but removed itself from consideration.

CHAPTER II

THE SSC AND THE PUBLIC INTEREST

The Superconducting Super Collider serves several public interests. Some are simply unmeasurable, while others cannot be measured directly. Because of the measurement problems, this analysis of the risks and benefits concentrates on how the SSC fits into the current federal portfolio of basic science research, whether the SSC favors instrument-intensive science, and which technologies are most likely to be helped by the SSC and to what extent.

BASIC SCIENCE AND THE PUBLIC INTEREST

In his analysis of the relationship of basic research (as opposed to mission-oriented research) and society, Leon Lederman, the director of the Fermi National Accelerator Laboratory, puts forward four overlapping reasons why these projects are in the public interest:[1]

- They provide the intangible benefit of general knowledge;
- They help recruit and train the next generation of scientists;
- They provide knowledge that eventually may have some practical application; and
- The process of solving scientific problems can produce collateral knowledge and instruments that may be useful in areas other than the original fields.

1. Leon Lederman, "Viewpoint from Fundamental Science" (report prepared for Fermi National Accelerator Laboratory, February 1982). For a similar analysis, see Leon Lederman, "The Value of Fundamental Science," *Scientific American*, vol. 251, no. 5 (November 1984), pp. 40-47.

Intangible Benefits

Science can be enjoyed for its own sake. There are science publications for the nonprofessional, science pages in the daily press, and even popular science television shows. Basic science research helps satisfy a human thirst to understand the universe. Such research also increases the knowledge of the general public and sets standards for the discipline of scientific inquiry, which may carry over into other aspects of cultural life. In addition, the United States derives substantial international prestige from its scientific accomplishments. These unmeasurable benefits, however, provide no substantive basis for ranking spending on basic science projects, other than inherent popular appeal.[2] Since scientific progress is, by and large, a slow and cumulative process, rankings based on popular appeal seem inconsistent with long-range planning.

Training Scientists and Technologists

Basic research inspires and trains many scientists and technologists.[3] This argument maintains that it is in reading about the big bang, dinosaurs, and other awe-inspiring, but not necessarily practical, expressions of science that each generation is recruited to science. More importantly, scientific training beyond undergraduate college courses often occurs working with professors on academic (meaning basic) science. Graduate students working on these projects move into industry where their training may be useful.

This criterion for support, however, does not help decide among alternative sciences each bidding for the federal dollar. Presumably, most good basic research projects will train the junior scientists and graduate students in their discipline. On the other hand, some

2. While it is possible to say that one given experiment is more important for the progress of physics than another, it is difficult to say whether advancement in physics is more important for the advancement of human knowledge than advancement in biology or any other basic science endeavor.

3. The president of the National Academy of Sciences, Frank Press, recently argued that "preserving the human resource base" in science should receive the highest priority in science budgeting. See Frank Press, "Sorting Through the Stress and Internal Dissension of U.S. Science and Technology," *New Technology Week* (May 2, 1988).

research programs may train more graduate students than others for the same level of spending.

Even so, the number of scientists and technicians involved in a project is not necessarily the only indication of the aggregate level of training. For instance, in the early 1970s, much of the output of accelerators was photographic plates (much like the cover of this report), which were then inspected visually to find particular patterns. This procedure was relatively labor intensive. Computer programs that recognize patterns now accomplish the same task much more rapidly with much less direct labor. While this example is extreme, replacing direct labor with equipment and technology occurs in all projects. The amount of labor varies with the technology of the science, and with the cost of labor compared with the cost of the technology. Judging the training benefits of a scientific program by counting heads fails to acknowledge this dynamic process. Funding projects entirely on this basis could also provide the incentive to use obsolete, labor-intensive methods of research.

Some argue that it is on large projects like the SSC that labor-saving scientific technology is developed. It is not so pressing to automate instrumentation in small science, this argument alleges, because there are no significant economies of scale to be realized. Yet, once developed by large projects, the labor-saving techniques can spill over to smaller projects.

With these caveats in mind, it should be noted that the field of high-energy physics does not train a substantial number of scientists. DOE estimates that currently 600 graduate students nationwide are studying high-energy physics. By contrast, in 1986, there was a total of 102,000 Ph.D. students in science, excluding psychology and social sciences. Thus, high-energy physics accounts for only a small fraction of science education in the United States. In addition, the number of technicians working on high-energy physics projects is comparable to the number of graduate students studying high-energy physics.[4]

4. Calculated from Department of Energy, *Report of the HEPAP Subpanel on Future Modes of Experimental Research in High Energy Physics* (July 1988), pp. 3 and 26. The number of engineers and technicians working on high-energy physics projects is assumed to equal 29 percent of the number of physicists plus physics graduate students. For the total number of Ph.D. students in physical science, see National Science Board, *Science and Engineering Indicators--1987* (November 1987), p. 196.

High-energy physics, therefore, does not provide a substantial number either of technicians or of graduate students, relative to its level of federal funding.

Practical Applications

Numerous examples of the links between basic science and practical applications exist. Solid-state electronics would be impossible without the knowledge of quantum mechanics, which was at the frontier of particle physics early in this century. The discovery of the genetic material DNA preceded its biotechnology applications by decades. The relationship between basic and applied research, however, is often oversimplified. Conventional analysis presents a pipeline where discoveries flow from basic research to applied research, and then to product or process development. The interaction of the different phases of research are actually much more complex. Sometimes it is in the application stage that gaps in basic research findings become apparent, or that solutions to these problems suggest themselves. In part because of the lack of a simple relationship between basic research and later research, there is no simple relationship between research and development and economic growth.

The output of both basic and applied research is information. In neither case is the information used directly by the final consumer. Both are used as an input to developing a product or process. From an economic perspective, one can think of the entire R&D process as a sequential search for the products or processes with the greatest economic utility.[5] Basic research narrows the search. Applied research further restricts the range of feasible applications. Development is the selection of one or more discoveries for commercial introduction. Overall, roughly two-thirds of R&D costs cover development.[6]

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5. Paul A. David, David Mowery, and W. Edward Steinmueller, "The Economic Analysis of Payoffs From Basic Research--An Examination of the Case of Particle Physics Research" (policy paper prepared for the Center for Economic Policy Research, Stanford University, January 1988), pp. 18-24.

6. For a more complete discussion of categories of R&D, see Congressional Budget Office, *Using Federal R&D to Promote Commercial Innovation* (April 1988), p. 34.

Analyses of basic science often fail to indicate that it is costly to use basic science results. To use the information produced by basic research, an organization must already possess a great deal of information, usually in the form of highly educated, and therefore expensive, employees. Thus, basic research has two cost components: discovery and use. In this sense, investments in basic research parallel investments in productive equipment: there is a fixed purchase cost and a variable use cost.

Because of these additional costs, the benefits derived from basic research must be put in perspective. For example, while modern solid-state electronics might be impossible without knowledge of quantum mechanics, it is also the case that with only the knowledge of quantum mechanics, modern solid-state electronics would also be impossible. Analyses that try to attribute all the benefits of these subsequent developments to basic research are overstating the contribution of basic science.

Technology Spinoffs

In many cases, the instruments created to perform science experiments have uses far beyond their original purpose. For instance, particle accelerators, which were originally developed to conduct physics experiments, are now used in areas as varied as medicine and the manufacture of integrated circuits. Already, the research performed for Fermilab's Tevatron I accelerator on superconducting magnets is having spinoffs for medicine via superconducting magnets, independently of the new research on high-temperature superconductors.

Several themes relevant to the SSC can be drawn from a substantial literature concerning federal government technology spinoffs and commercial innovation.[7] (For a discussion of technology spinoffs from government programs, see Appendix A.) First, federal agencies have had the greatest success with spinoffs when they were users, not just champions, of the technology in question. Second, federal agen-

7. For a compendium of industry studies, see Richard R. Nelson, ed., *Government and Technical Progress, A Cross-Industry Analysis* (New York: Pergamon Press, 1982). See also Kenneth Flamm, *Creating the Computer: Government, Industry and High Technology* (Washington, D.C.: The Brookings Institution, 1988), and *Targeting the Computer: Government Support and International Competition* (Washington, D.C.: The Brookings Institution, 1987).

cies also played a substantial role in commercial development when they represented a large fraction of total demand for a given product. Third, while federal agencies may have played a crucial role in the development of technologies, individual programs or instruments are rarely responsible for the entire development: progress generally comes one step at a time. Lastly, even when a general area of development seems promising, an individual area may not be.

These points have several lessons for the SSC. Most important is that the SSC by itself is unlikely to result in more than one or two major technological developments. This limitation is, however, not inconsistent with continued support of basic research for the sake of technology spinoffs: while the Congress may expect the field as a whole or science as a whole to provide net benefits to the nation, the likelihood of an individual project doing so is quite small.

Second, the fields of technology in which the SSC is likely to play a role are probably limited. The SSC will represent the bulk of the superconducting magnet market during its construction. Consequently, from the perspective of both technology push and demand pull, the SSC may prove important to the development of a superconducting magnet industry. This is not to say that the SSC will not contribute to technical progress outside this field: rather, the SSC is similar to any other sophisticated consumer of computers and instruments, and it is no more or less likely to produce an important advance than any other major laboratory. (Some studies of CERN accelerator programs have tried to assert the contrary, but analysis of these results shows these claims are overstated. See Appendix B for an analysis of spinoffs from CERN accelerator research.)

THE FEDERAL SCIENCE PORTFOLIO

In the context of the federal budget for science, the SSC can be evaluated in terms of how it might produce scientific results that could be of use in the future. Because the SSC would be a basic science laboratory, the discussion focuses not on near-term use of the project results (not even the most ardent advocate believes SSC results will be useful in a practical sense in the near term), but on the amount of science it produces for the cost. Unfortunately, knowledge does not come in measurable units, but related measures can provide an indication of the possible benefits. Such measures include the application of basic scientific knowledge, the relationship between scientific input (people and money) and expected outputs, and the diversification of the federal science portfolio.

The SSC would occupy a substantial portion of the entire federal budget for basic science. Construction costs for the SSC will average roughly $600 million annually for six years. By way of comparison, in 1988, federal agencies are projected to spend $9.0 billion on all basic science research, but only $4.5 billion on basic research excluding the life sciences.[8] Assuming unchanged levels of real funding, the SSC would account for between 6 percent and 7 percent of the entire basic research budget and 13 percent of the physical sciences budget for over half a decade, doubling the share of the science budget going to particle physics. Unless the Congress provides for substantial growth in other relevant research agencies, the SSC may very well crowd out other basic science research. Considering the high rejection rates in science agencies--the National Institutes of Health, for instance, funds only one-third of new grant applications that have passed peer review--the knowledge that is expected to result from the SSC must be central to the advancement of particle physics in order to justify its level of funding.

One aspect of basic research that is often misunderstood is its riskiness. In "normal" times, scientists know roughly what they are looking for: they are attempting to validate or disprove results derived by theory or obtained by their colleagues.[9] For instance, before new subatomic particles are discovered, their mass and characteristics are usually known well enough to tell phenomenologists--the physicists who interpret accelerator output--what to look for. Instrument technology is also improved in a gradual manner--for instance, the SSC design is largely derived from experience with the Tevatron I accelerator at Fermilab. Thus, a large part of the risk is neither scientific nor technological. Rather, from the perspective of the public interest,

8. *Budget of the United States Government, Fiscal Year 1989, Special Analyses*, p. J-7.

9. "Normal" science makes a small individual contribution to a paradigm, like a piece in a puzzle, that fills out a complete picture.

the risk is economic: that the investment will produce nothing commercially useful.

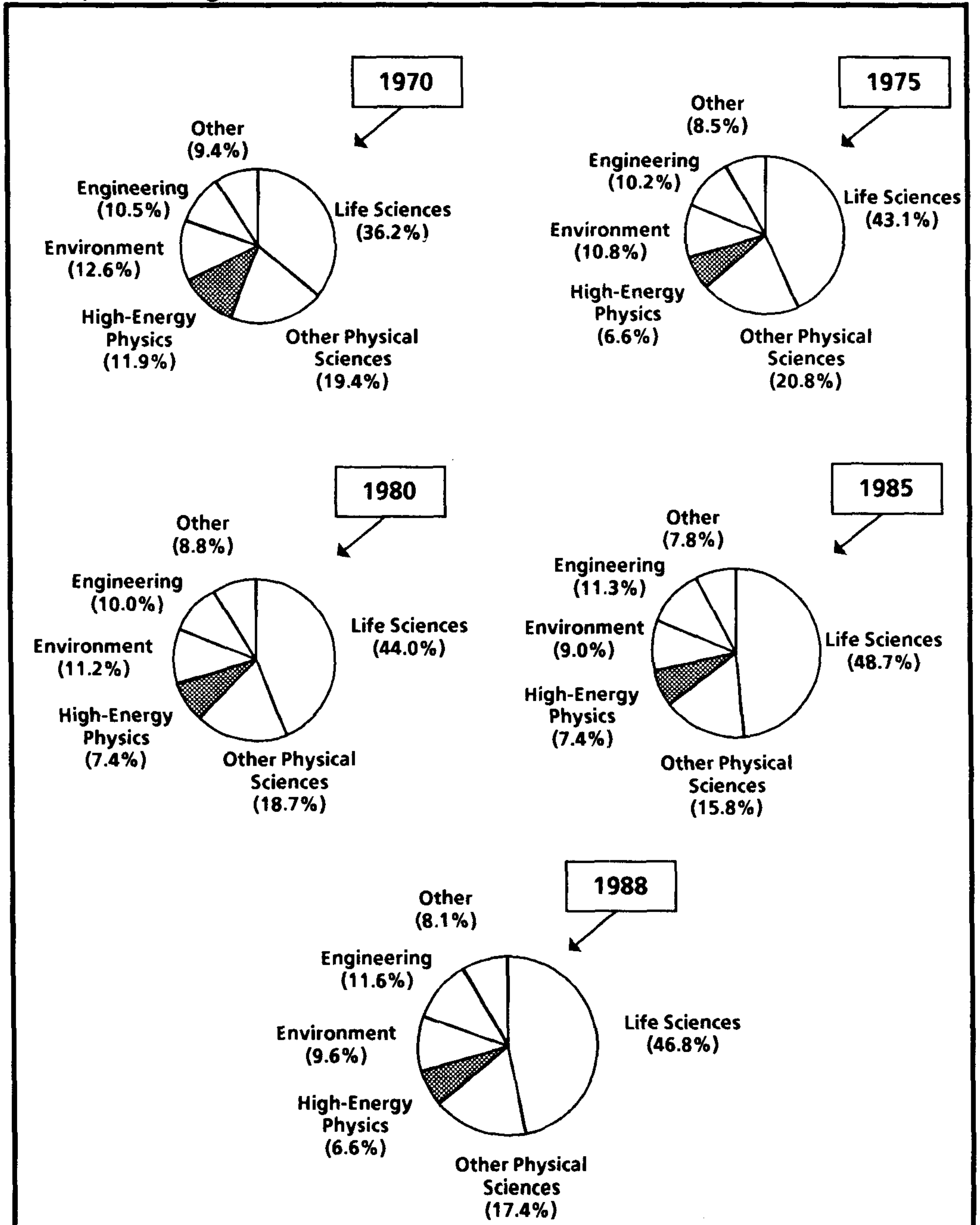
One response to the risky nature of science spending is to maintain a diversified portfolio of science investments. Since no one knows which basic science will provide the most useful results or even, in actuarial terms, what the pattern of returns to basic science is, one reasonable strategy is to invest equally in all sciences. This strategy can be static, giving each science a fixed percentage of the basic science budget, or dynamic, responding to perceived breakthroughs or opportunities, while maintaining a balance over time. By and large, the Congress has attempted to expand developing areas, as shown by the effort to increase research in superconductivity in response to the new discoveries. A corollary of the dynamic portfolio mix is that as fields are exhausted, federal investment should be reduced.

Figure 1 shows the share of federal basic science funds by scientific discipline for selected years. The portfolio clearly favors life sciences, whose share has risen from 36 percent of the total in 1970 to about 47 percent in 1988. Fully half of this rise came at the expense of high-energy physics, whose share has declined by more than 40 percent over the same period (from 11.9 percent to 6.6 percent). Figure 1 also shows that the big declines in the share of the budget allocated to high-energy physics came in the early 1970s (presumably after the war on cancer concentrated research in related fields).[10] The share of the science budget devoted to high-energy physics rose from a low point of 6.6 percent in 1975 to 7.4 percent in the early 1980s. Since the construction of the Energy Saver and Tevatron I at Fermilab, however, this share has returned to the 1975 level.

In the case of high-energy physics, this relative decline was also a real one. In constant 1988 dollars, high-energy physics spending fell

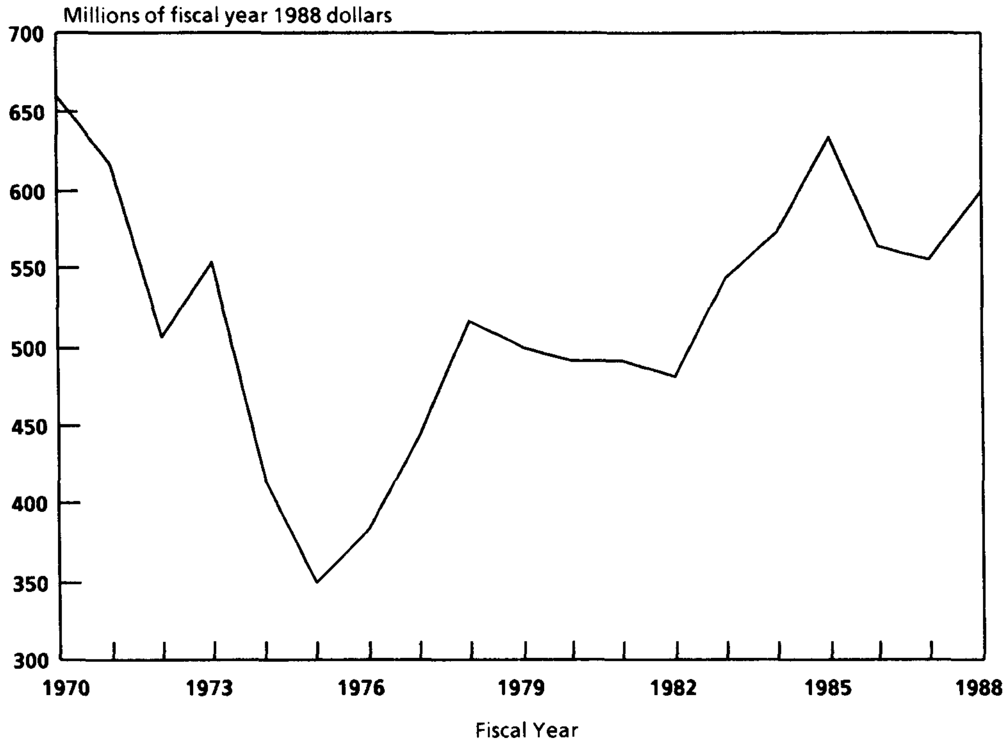
10. Interestingly, the share of basic science spending that went to engineering and medicine, which are applied fields, increased during this period, raising questions about definitions. If the definition of basic science--as used by reporting federal agencies--changed over the period, then relative shares may be shifting for different reasons. This may especially be the case with medical research, for which the share quadrupled between 1967 and 1986, or engineering, for which the share rose by a factor of six. On the other hand, while the war on cancer increased research in many applied fields, it also increased the desire to learn more about basic biology. For detailed information about basic research spending by field of science, see National Science Board, *Science and Engineering Indicators--1987* (November 1987), p. 252.

Figure 1.
Basic Science Budget by Discipline for Selected Fiscal Years
(As a percentage of all federal basic science research)



SOURCE: Congressional Budget Office, derived from data provided by the National Science Foundation, the Department of Energy, and the National Academy of Sciences.

Figure 2.
High-Energy Physics Spending



SOURCE: Congressional Budget Office, derived from data provided by the National Science Foundation, the Department of Energy, and the National Academy of Sciences. Numbers adjusted for inflation using the gross national product deflator.

from $660 million in 1970 to $600 million in 1988, a 10 percent decline. Figure 2 shows, however, that high-energy physics spending has been growing in real terms since its nadir in the mid-1970s.[11]

This relative decline in the funding of particle physics is consistent with a diversified portfolio strategy of basic science only if particle physics is in stagnation or if life sciences are perceived as being able to provide more usable science. Observers would probably agree that particle physics has not been stagnant during the last two decades, nor is it now. Life sciences must therefore be perceived as being able to produce more usable results, although this perception is

11. Using sectoral deflators instead of the gross national product deflator would produce a generally similar pattern.

inconsistent with the notion that policy cannot judge beforehand which basic science will prove the most useful. Biotechnology itself is in part derived from the particle physics--quantum mechanics--of the early twentieth century.

On the other hand, the Congress may be expressing a sense that particle physics may have hit a point of diminishing returns in terms of producing results usable within a few decades.[12] This is not to say that particle physics will produce ever-decreasing knowledge, but rather that particle physics may become justified by its intangible benefits, rather than by the practical application of its scientific results. (Of course, high-energy physics may still produce economically useful technological spinoffs.) The phenomena the accelerators now seek to describe may be so fundamental that, like the theories about the big bang or the extinction of the dinosaurs, they become part of the culture, not the economy. This belief would come from a perception that, rather than all basic science being the same, some research is more basic than others.[13] But this further division of basic research simply modifies, rather than solves, the dilemma: how does the Congress decide among very basic research projects?

ECONOMIES OF SCALE IN BASIC SCIENCE

Roughly 1,500 Ph.D.-level particle physicists are active in experimental work in the United States, two-thirds of whom are based at universities.[14] Universities contain a further 700 elementary particle theorists and 600 graduate students in particle physics, making a national total of 2,200 particle physicists. By contrast, in 1985--the most recent year for which numbers are available--72,200 Ph.D.-level scientists were working in all fields in the United States.[15] (Psychol-

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12. For a technical version of this argument, see John F. Waymouth, in "Letters," *Physics Today*, vol. 41, no. 7 (July 1988), pp. 9 and 11.

13. Leon Lederman describes this as "very basic" research. See Lederman, "Viewpoint from Fundamental Science," p. 3.

14. Calculated from Department of Energy, *Report of the HEPAP Subpanel on Future Modes of Experimental Research in High Energy Physics* (July 1988), pp. 1-3. Other DOE sources give similar numbers (within 10 percent to 15 percent).

15. National Science Board, *Science and Engineering Indicators--1987* (November 1987), p. 274.

ogists and social scientists account for 9,800 of these.) Thus, while particle physics represents only 3 percent of practicing scientists, it accounts for over 6 percent of science spending.

Whether more "science" takes place in large science facilities or in individual laboratories is difficult to determine, and the debate is not clearly productive. Some science questions lend themselves to small research projects and others cannot be answered by anything other than the largest pieces of equipment. Given these constraints, the scientific trade-offs become less clear. For instance, it may simply be impossible to investigate some areas of astronomy without very expensive pieces of equipment. If U.S. scientists are to work in these areas, certain large investments must be made. While the scientific trade-offs are not clear, the budgetary trade-offs are: money that goes to large instruments is not available to fund smaller-scale projects. Thus, the Congress is being asked to make choices that scientists themselves admit they are unable to make in terms of science output.

Economies of Scale in Particle Physics

Evidence suggests that particle physics is one of those fields where large instruments are the rule.[16] According to a recent Congressional Research Service survey, there are over 200 "big science" facilities or instruments--defined as costing more than $25 million in fiscal year 1984 dollars--in the United States.[17] Of these, 17 are for particle physics. In addition, most, if not all, particle physicists use these existing instruments, or their output. For instance, over 50 percent of high-energy physicists in this country use Fermilab's Tevatron complex, which is the largest accelerator currently available.[18] Furthermore,

16. High-energy physics investments may be what economists call "lumpy"--that is, investments with an indivisible input. Just as it is impossible to discover one-quarter of a new world, it may be impossible to discover a use for one-quarter of a theory of quarks or the electroweak force. For the implications of this, see Paul A. David, David Mowery, and W. Edward Steinmueller, "The Economic Analysis of Payoffs From Basic Research--An Examination of the Case of Particle Physics Research," pp. 25-27.

17. See Congressional Research Service, *World Inventory of "Big Science" Research Instruments and Facilities* (December 1986).

18. Statement of Leon Lederman, Director of the Fermi National Accelerator Laboratory, before the Subcommittee on Energy Research and Development, Senate Committee on Energy and Natural Resources, Hearings on the Department of Energy's fiscal year 1989 budget request for the Superconducting Super Collider and the Basic Science Budget, April 12, 1988.