Science in America

Since World War II the United States has spent more than $500 billion on research and development, and U.S. achievements in particle physics, genetics, astronomy, agronomy, and other fields have been unprecedented. (Americans have won nearly half of all Nobel Prizes awarded for science since 1946.) But congressional critics and increasing numbers of scientists now question the direction of the American science effort. Should research be targeted toward more immediate, practical goals? Are the big research universities outmoded? Do we need new types of scientific institutions? The current debate has a peculiar history. In the 19th century, American scientists lamented the contemporary emphasis on practical science as well as the new republic's lack of a European-style university tradition. The surprising thing about American science, in their view, was not that it had made so *little* progress but that it had made so *much*. Here historian Nathan Reingold reviews the rise of American science; Philip Abelson, a physicist, chemist, and geologist, describes its new frontiers; and John Holmfeld, a congressional staff specialist, reports on the shifting focus of federal science policy.

O PIONEERS!

by Nathan Reingold

In 1800, the score of professional scientists in the United States was scarcely distinguishable from the somewhat larger group of devoted amateurs—like the gentleman-scholar Thomas Jefferson and the multi-talented Benjamin Franklin. As befitted a nation of farmers, sailors, and craftsmen, most Americans pursued such sciences as zoology, botany, geology, and astronomy—sciences rooted in the world around them. There was a constitutional mandate to "promote" the useful arts and sciences by regulating patents and copyrights, but the federal government's involvement in science was otherwise haphazard, tied to Antarctic naval expeditions or the western explorations of Lewis and Clark.

Today there are 500,000 American scientists in research and development alone, with 1 million more in other scientific or technology-based fields. Annual private and federal spending on research and development exceeds $40 billion. And astronomy, botany, and the rest have been joined by a host of other disciplines so diverse and some of them so arcane that one might now define a "generalist" as a scientist who knows his own sub-speciality and one other sub-specialty. Despite this fragmentation of knowledge, U.S. science and technology have no peer.

How did the United States get to be No. 1? That seems like one question but it is really a dozen. A comprehensive answer must consider the progress of scientific knowledge, which may have a certain logic in retrospect, as well as the evolution of federal subsidies for research, which does not. An explanation must include the development of European science and the growth of American industry, education, and national wealth. The discussion must encompass the recurrent public controversies over what "science" really is and over the long-term value of "basic" versus "applied" science. And it must note the persistent insecurity in the broader American scientific community over its own status in society.

These factors are easier to identify than to put together. Physicist Samuel P. Langley observed in 1888 that we often hear scientific development "likened to the march of an army towards some definite end; but this, it seems to me, is not the way science usually does move. . . ." A better metaphor might be to compare these forces to ocean waves of different frequency that suddenly get "in step" to produce a giant wave with extraordinary momentum.

Such waves are preceded by deep troughs. Until the Civil War, the United States depended, in scientific terms, largely on Western Europe. "Who reads an American book?" asked the

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English wit Sydney Smith in 1820. There was some good native science—Nathaniel Bowditch's work in mathematics and navigation comes to mind—but not much. If the natural philosophers ("scientist" was a word not coined until 1840) in Paris and Berlin thought much about the United States, then like the great German naturalist Alexander von Humboldt they thought of it as a vast natural laboratory rather than as a place to build one.

From Telegraph to Cyclotron

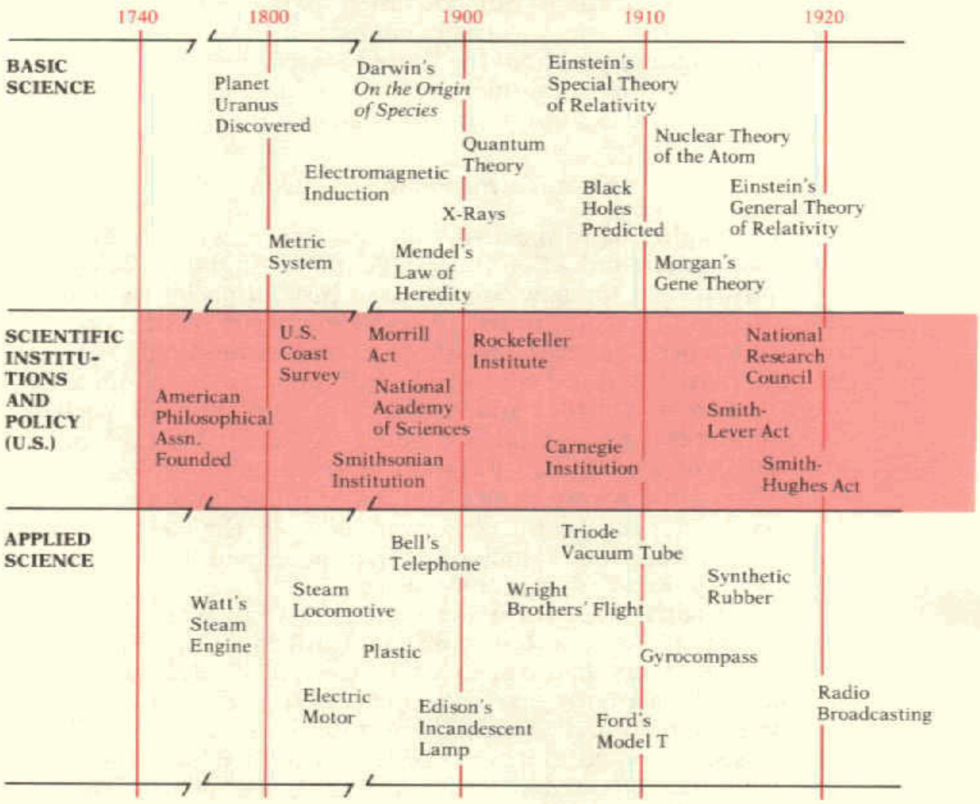
But beginning in the 1840s, Joseph Henry, who discovered electromagnetic induction independently of England's Michael Faraday, turned the new Smithsonian Institution into a center for "abstract" science. In the 1860s Yale granted its first doctorate in science (the second would go to the outstanding theoretical physicist J. Willard Gibbs). The U.S. Department of Agriculture was created in 1862 and, through a system of tax-supported land-grant colleges established under the Morrill Act, planted the seeds of a sustained program of research in biology and chemistry—the government's first major plunge into the world of basic science. As the Army opened up the West, geologists and naturalists, including the one-armed John Wesley Powell, explored the virgin territories.

American science leapt ahead after the Civil War. Although mathematician Simon Newcomb could still complain that not a single U.S. entry had appeared in Germany's *Jahrbuch der Mathematik* in many years, the general record in just about every other field had improved enormously. In 1865, Britain's Royal Society noted in its catalogue that the backward American republic accounted for no less than 5 percent of all scientific articles published.

Before the Civil War, America's industrial revolution had done little to advance basic science. To be sure, the mills were humming and "every spindle turning," as Hezekiah Niles's *Weekly Reporter* observed in the 1830s, but industry as yet had little use for the scientific disciplines. Then, with the 1870s came the expansion of the Gilded Age, the steam-powered railroads and factories. A nation of inventors and tinkerers had turned into a burgeoning industrial giant. Crotchety Henry Adams would rail against the "dynamo," but scientists and engineers rallied to its support, as did most laymen.

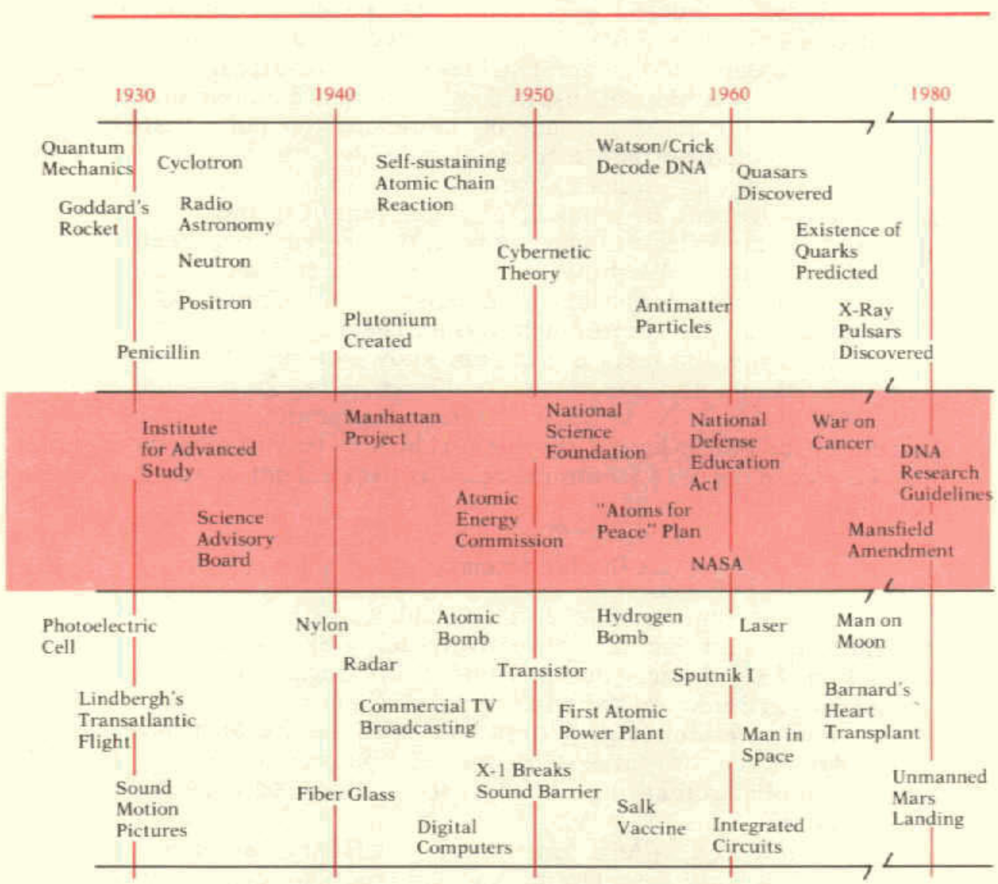
In practical science, Bell and Edison gave us electrical sound and light. In abstract science, America began to approach parity with Europe. Swiss-born Louis Agassiz pursued important researches into rocks and fossils while creating Harvard's

DEVELOPMENTS SINCE 1740 IN BASIC AND APPLIED SCIENCE



Museum of Comparative Zoology. J. Willard Gibbs was working in thermodynamics; geologists James Hall and James Dwight Dana studied mountain formation and coral structures. In 1877, with the new 26-inch refractor telescope at Washington's Naval Observatory, astronomer Asaph Hall discovered Deimos and Phobos, the two satellites of Mars. Two years later, A. A. Michelson measured the speed of light.

From the 1890s on, the pace of discovery accelerated. Working closely with their European colleagues, American scientists began to explore the structure of the atom. In 1906, Lee De Forest ushered in the age of radio with his triode vacuum tube. In 1910, T. H. Morgan launched what is now called "classical



genetics" based on experiments with the fruit fly, *Drosophila melangastor*. A year later, Robert A. Millikan, who like other Americans of his generation had studied in Germany, calculated the electric charge on the electron.

In the next decades followed the early work in computers; the world of high energy physics opened by E. O. Lawrence's 1931 cyclotron; the discovery in 1932 of the neutron and positron; and the isolation, that same year, of deuterium by Harold Urey at Columbia. In 1944, Oswald Avery demonstrated that DNA was the material carrier of heredity. From the turn of the century through the Depression and World War II to the present, the story is one of continuous growth. Such projects as the atomic bomb, nuclear energy, and the space program not only demonstrated sophistication in engineering and technology; they also depended on great strides in basic research.

Oddly, success has not inspired self-confidence among our scientists. Despite the assurance of public-opinion polls that they are respected by the American people, despite the heavy outlays of taxpayers' dollars devoted to research, despite the publicized advances in particle physics, genetics, and electronics, they fear a slackening of support; they agonize over real or predicted cuts in Washington's "basic research" spending. They shake their heads over the shrill polemics of the anti-DNA, anti-nuclear, and pro-environment absolutists. And as if to confirm their own worst fears of rampant know-nothingism, they sometimes take a perverse satisfaction in surveys like the poll conducted by *The Times* of London, which showed that while 15 percent of the public have faith in a "scientific" way of reasoning, 42 percent believe communication with the dead is a fair possibility.

A Double Strategy

If we could communicate with the dead, we would probably find that American scientists have always felt a bit insecure. As far back as 1832, physicist Joseph Henry decried what he saw as the nation's attitude toward what he called "abstract" science. In his view, a nation of go-getters had little use for abstract knowledge. Even its name—"abstract," "basic," or "pure" science—implied something valued for its own sake, of no use to a wider public.

Alexis de Tocqueville, a contemporary of Henry, contended that Americans would excel in the world of practical science but would never rise to theoretical eminence. Just as it was thought that a democratic society could produce popular or "vernacular" cultures but not "high" ones (an aristocracy was required for that!), so it was felt that Americans would always make a better mousetrap but would never add much to the world's knowledge of mice.

Henry feared what Tocqueville took as fact. Behind his fear was a belief that technological achievement depended on the advance of abstract science. In the America of the 1840s, to the extent that basic research existed at all it was usually scrambled together into applied fields. There were no graduate schools and only one research institute—the Smithsonian, founded in 1846 and headed by Henry. The age of the learned and professional societies such as the National Academy of Sciences still lay in the future. In one sense, the American situation was unenviable; in another, it was an opportunity.

To counteract this perceived neglect of basic science, the leading American scientists of the pre–Civil War era evolved two deliberate strategies to advance theoretical knowledge while at the same time taking care of the utilitarian needs of a growing industrial society. That is to say they defined both a "broad strategy" and an "enclave strategy."

Jefferson's Precedent

The enclave strategy evolved before the Civil War when Joseph Henry designed the Smithsonian Institution—despite bitter opposition from those who wanted only a museum and library—as America's first center for abstract research sheltered from the pressures of immediate industrial or social demands.

This approach was continued by such organizations as the Rockefeller Institute (1901, now Rockefeller University), the Carnegie Institution (1902), and the Institute for Advanced Study at Princeton (1930). It persists today in some government labs and in the federally funded, specialized centers within the great research universities, such as the Scripps Oceanographic Institute at the University of California. Here, the emphasis is largely on pure science pursued for its own sake.

While Henry struggled with the Smithsonian, his friend A. D. Bache framed a broad approach to take advantage of the already "mixed" character of applied and basic science. A great-grandson of Benjamin Franklin and first president of the National Academy of Sciences, Bache for years headed the Coast and Geodetic Survey, whose function was to issue maps and charts.

Bache's idea was simple. Americans, he felt, would never support scientific institutes like the Smithsonian to the degree that kings and aristocratic patrons supported such centers in Europe. But government agencies like the Coast Survey and the Army's Topographical Engineers had statutory missions that, with a little imagination, could be defined to include substantial amounts of abstract science. Essentially, Bache was following Jefferson's strategem. As President, Jefferson had defended the Lewis and Clark expedition in Congress on commercial grounds; to the Spanish Minister, through whose territory the party would have to pass, he described it as a geological mission.

In the Coast Survey, for example, Bache defined seismology, terrestrial magnetism, and other subjects as essential to the routine production of high-quality maps and charts. Similarly, when the Smithsonian reluctantly acquired museum functions, Henry and his successors continued to sponsor basic research, seeing it as necessary for quality control in public exhibits. Finally, the creation of state agriculture colleges, designed to improve American farming techniques, inevitably led to research into genetics, soil chemistry, and climate.

What happened was this: In theory, American science maintained a distinction between applied and basic research; in fact, it maintained the distinction only in theory. Like the earth and the moon, the two were distinct yet inseparable, influencing and reinforcing each other in subtle ways. Vannevar Bush's work with practical engineering equations led him to develop the differential analyzer, which ultimately had theoretical implications. And Irving Langmuir's theoretical work in electron emission produced a better light bulb.

The Rise of the University

This tandem pursuit of basic and applied science was one of the vital differences between the evolution of European science and that of its precocious child in the New World. In Europe, the two were pursued as a bifurcated effort. In America, with some exceptions, they never really were. This mixture remained even when the rise of the elite universities, philanthropic foundations, and science-based industries in the 20th century combined to eclipse government-conducted research.

By 1900, for example, there were more physicists in American universities than in those of any other country, and their numbers were growing faster than anywhere else outside of Japan. Rising proportions of high school graduates swelled college enrollments. (In 1900, 6.4 percent of the population had graduated from high school; in 1940, more than half.) With the pioneering success of Johns Hopkins University, graduate schools flourished. By 1940, the 382 doctorates granted annually in all fields at the turn of the century had increased by 1000 percent.

More important, the universities branched out to service every cranny of an increasingly complex industrial society. To be sure, scientists still pursued the higher mathematics; astronomers gazed at the stars; and physicists followed closely the theoretical work of Albert Einstein and Niels Bohr and Ernest Rutherford. But university scientists also developed hybrids of corn and new kinds of wheat to feed a growing population. In short, even as they followed their noses into the theoretical unknown, scientists looked around en route for ways to harness

THE FIRST DEBATE

Americans are now used to scientist-advocates, be the issue recombinant DNA, the environment, or nuclear safety. But the phenomenon is a recent one; until the first debate in the late 1940s over the military use of atomic energy, U.S. scientists had kept a low profile.

Was the atomic bomb a breakthrough or a breakdown? After a first flush of enthusiasm, scientists began to wonder. One group, headed by physicist William Higinbotham, launched the apocalyptic *Bulletin of the Atomic Scientists*, whose "clock" logo showed war inching ever closer. (The examples above are from before and after the first Russian atomic blast in 1949.) Others, including the "father" of the bomb, J. Robert Oppenheimer, drew up what eventually became the Baruch Plan (1946). The plan called for destruction of all nuclear weapons, with peaceful applications of atomic energy to be regulated by a new international agency. It was rejected by the Soviets.

America's only recourse was to stay ahead in the arms race. So argued those leading scientists (such as Edward Teller and E. O. Lawrence) who helped create the hydrogen bomb. Though opposed by Oppenheimer, Enrico Fermi, and Hans Bethe (Fermi wanted to "try once more" for disarmament), an American H-bomb was detonated in 1952; the Soviets followed suit in 1953. It was not a halcyon time for liberal physicists. As historian Daniel Kevles later noted, scientists were still listened to by the government, "but the voice most listened to seemed to be Edward Teller's." Later debates arose over nuclear testing and the neutron bomb.

what they found; when harnessed, it sometimes pulled them further.

Science was soon to acquire a home in industry as well when the work of such practical wizards as Edison and Bell took corporate form in the shape of ambitious new companies like General Electric and Bell Telephone. There was no mistaking the motives of these companies—they wanted profits. But technology does not exist in a vacuum; pure research was regarded as an essential component of scientific commerce. In 1927 H. D. Arnold, then president of Bell Laboratories, put the matter succinctly. Bell was interested, Arnold wrote, simply in producing more electrons to run its radios and telephones and, soon, its television sets. And Bell wanted its electrons cheaply. But the best road to this end, Arnold explained, "must include a thorough understanding of the broad facts of electron emission." Work in this area won Bell Laboratories' physicist C. J. Davisson the Nobel Prize (1937). Bell received another Nobel for developing the transistor (1956).

Policeman and Paymaster

What developed in the United States was a phenomenally diverse scientific enterprise, and in diversity it found vitality. Basic research was conducted not only by a few specialized federal agencies but by industry and the universities as well. It was paid for not only by the government but also by private philanthropy, by the great foundations, by university tuition, by industry, and by ordinary citizens who put down hard cash for a new radio, television, or telephone. And it so evolved that the accretion of new theoretical knowledge was often taking place on the same workbench, so to speak, where technicians and engineers were trying to turn theory into something men could use. There was little chance, despite the fears Lyndon Johnson voiced in 1966, that new scientific innovations would be "locked up in the laboratory." Indeed, some Americans now seem to fear that some discoveries will *not* be locked up.

Does all of this help to explain the evolution of American science? Some skeptics will surely note that the facts of history are like the letters of the alphabet—you can make them spell what you want. Others might contend that the rise of American science is essentially the same success story we have witnessed in Russia and in Japan: A rich nation's investments paying off.

And yet the special elements of the American story—the driving insecurity of scientists, the complementary broad and narrow strategies, the diversity of effort, the pragmatic partnership of science with education and industry—are too clear to be ignored. Even when, during World War II, the federal role in science took a quantum leap, and even after the government became both a policeman and a paymaster of science, these phenomena continued to shape American science and science policy.

Samuel Langley was right: Scientific progress in this country has not been the march of an army toward a goal clearly in sight. Instead, it has been something less controlled—and therefore, perhaps, more open to initiative and imagination. "In this Democratic Country," Joseph Henry observed, "we must do what we can when we cannot do what we would."

THE NEW DISCOVERIES

by Philip H. Abelson

Very little human activity ever proves of much consequence in the anarchic scheme of history, and, whether fortunate or not, the fact is nonetheless irksome; men do not like to be told that they are plowing the waves.

The Roman poet Horace ventured one solution: Through art, he claimed, one could erect a monument "more permanent than bronze"—and he was right, at least in his own case. But today men are building a collective, not an individual, monument: the edifice of scientific knowledge.

The edifice has unusual properties. It is constantly being extended, tested, perfected. Ornaments are added regularly—and as regularly erased. Most unusual of all is that the edifice is being constructed by hundreds of thousands of people who, relying on standards implied in the term "scientific method," can build confidently on the foundations laid by others who may be thousands of miles—or hundreds of years—apart.

For that reason, if a scientist of 50 years ago suddenly visited a modern laboratory, he would undoubtedly be bewildered, but he could quickly be brought up to date. Unlike the wild boy of Aveyron, he would not have arrived as a blank slate in an alien culture. He would appreciate some of our pressing dilemmas—among them, that the more we learn, the less we understand. He would be at home, too, in the great areas of scholarly inquiry, though they have changed greatly since 1928.

Astronomers still observe the familiar stars but now perceive them as great nuclear reactors. They talk authoritatively of quasars, pulsars, neutron stars, and black holes, yet they hunger to know how the stars, the galaxies, and the universe were formed.

Plant biology remains of immense importance, but with our urgent needs for food and energy it has evolved from a descriptive science into an experimental one. Through biology and medicine we have eradicated some of the deadliest diseases known to man—most recently, smallpox—but the mechanisms of genetics elude us as before, and we have only just begun to understand how the mind and memory work.

The *tools* of the modern researcher might easily confound our visitor from 1928. He would be puzzled by most of the equipment in a modern research lab and astonished by the fact that the annual cost of equipment per U.S. scientist is in the tens of thousands of dollars. He would probably ask to sit down when told that throughout the world scientists speak to one another through an intricate network of teleconferencing, computer linkups, and, when necessary, the relatively mundane telephone—all made possible by continuing developments in electronics. Here we have seen a major leap forward since the 1920s.

More Nimble than the Brain

Electronics stands behind the space program and the computer. It will soon transform the banking industry, making it possible to commit errors in one's checkbook without lifting a pen. In the end, the electronics revolution will prove as important as the Industrial Revolution of the 18th and 19th centuries, though for different reasons. The Industrial Revolution was crude and based on large-scale energy use. The electronics revolution is refined: It bends energy and force to our will, much as the brain directs the use of muscles. Yet, for some tasks, electronics can be more subtle, more nimble, and more dependable than the brain.

In their simplest form, electronic measuring devices convert a physical quantity, such as light, into an electrical signal. (A familiar example is the exposure meter used in photography.) In more complex devices, the signals are further processed and decoded by medium-sized computers. In these devices thousands of miniaturized integrated circuits can now be molded into silicon chips the size of a fingernail. Each chip costs about $1.00. Sixteen years ago, an electronic device with similar capabilities would have cost $6,000. And it would have been 30,000

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THE MICROELECTRONICS REVOLUTION

Most of the technological achievements of the last two decades depend on microelectronics. Without microelectronic devices there would be no satellites, no MIRVed missiles, no reliable computers, television sets, or bank records as we know them.

In the beginning was the transistor, a small, low-powered amplifier that replaced the vacuum tube. Invented in 1948 by the team of John Bardeen, Walter H. Brattain, and William Shockley at Bell Laboratories, the transistor has now evolved into a complex arrangement of "solid-state" integrated circuits on a chip the size of a fingernail. In modern microelectronic devices the circuits are formed on these chips by photolithography, in some cases using a steered electron beam.

The theory behind integrated circuits is relatively simple. Some substances, including most metals, are excellent conductors of electricity. Others, such as rubber and glass, are poor conductors and can be used as insulators. In between are substances such as silicon that are known as semiconductors.

By introducing small impurities—a process known as "doping"—atoms of pure silicon can be given either a positive or a negative charge. If a silicon atom, which has four electrons in its outermost or "valence" shell, is doped with phosphorus, which has five electrons in its valence shell, the resulting linkup will generate one "free" electron. This extra electron is capable of carrying a negative charge and thus gives the semiconductor a negative (*n*-type) orientation.

The silicon atom can also be doped with boron, which has three electrons in its valence shell, to form a bond that is missing one electron, creating a "hole" that gives a positive (*p*-type) orientation. When an electric charge is applied to the semiconductor, the extra electrons and holes are mobilized to act as charge carriers.

As in the first transistor, the *p*-type and *n*-type semiconductors can be arranged in layers to conduct electric charges in only one direction within a circuit; thus the circuit may be either "on" or "off." A certain electrical "input" will give a predetermined "output"—an arrangement called a "gate" that is the basic unit of electronic logic.

A unit that can go on and off in a predictable fashion can also be made to represent "yes" or "no"—or 1 and 0, the constituents of the binary number system used in all computers.

times as big. What Thomas Carlyle said of men may especially be applied to the scientist: "Without tools he is nothing; with tools he is all."

The most glamorous new tool is the laser. A laser can be made to produce a steady stream of light, but is usually adjusted to emit an intense, controllable, monochromatic pulse that may be as short as one-trillionth of a second (one *picosecond*). These features permit sharp focusing of the light as well as precise timing.

Most Americans are now familiar with the use of a laser to repair detached retinas, cut steel sheets, or conduct high-accuracy land surveying. Some lasers are being used in endeavors to achieve nuclear fusion. But the most important applications will surely come in chemistry. Chemists have long known that some chemical reactions occur rapidly; in many instances, intermediate products are formed during a chemical process that may last for no more than one picosecond. (In some plants, the absorption of a photon of light takes *less* than one picosecond.) Lasers now are being used, in what is called *picosecond chemistry*, to make these reactions finally accessible to study.

Pulsars and Quasars

The laser is only one of many instruments that have increased the precision and speed of observation. At one time, for example, the chemical analysis of a typical rock required a one-gram sample and a week's time. The process resembled a python digesting a ram. The rock was first ground to a fine powder, then subjected to long periods of "digestion" by a mixture of corrosive acids until it was dissolved. A skilled chemist might complete a dozen analyses in a week. Today, using an electron microprobe, a sharply focused electron beam hits a tiny spot on the surface of the specimen and produces X-rays whose character will vary with that of the rock's constituent elements. These X-rays are then resolved and interpreted electronically. The process requires 10 minutes and one-billionth of a gram of rock.

In astronomy, intriguing new discoveries have come from the use of radiotelescopes—those dish-shaped receivers up to 300 feet in diameter that are exquisitely sensitive to radio signals reaching Earth from outer space. Until World War II, most astronomers had to rely on photographic plates to record their observations—a good technique as far as it went, rather like a silent movie about the Vienna Boys Choir. Now the great observatories have been converted into electronic laboratories, and their records are stored on magnetic tapes. Radiotelescopes helped astronomers determine the shape of our galaxy, the Milky Way—basically a flat spiral with a bulge near the center. Signals received by radiotelescopes also revealed that there were powerful radio stations in the sky, some of them switching

"BEAUTY," "TRUTH," AND "STRANGENESS"

In 1964 physicists Murray Gell-Mann and George Zweig independently predicted the existence of a fundamental, subnuclear particle that cannot be broken down into smaller constituents. They called the particle a *quark* (the word comes from James Joyce's *Finnegans Wake*), and theorized that quarks are building blocks that combine to form the atomic units known as *hadrons*, a family that includes protons, neutrons, lambdas, and mesons. (An unrelated family of atomic units, the *leptons*, includes electrons, neutrinos, and muons.)

Four types of quarks are currently believed to exist, distinguishable by the peculiar quantum characteristics of "up," "down," "strangeness," or "charm." All quarks have a fractional electric charge, angular momentum, and mass. For each type of quark there is also an *antiquark*, with opposite characteristics.

Quarks are characterized by their sensitivity to the so-called *strong* force that binds quarks together to form hadrons (the Greek word *hadron* means "stout" or "strong"). One up and two down quarks are combined by the strong force to form a neutron. One down and two up quarks form a proton. One up, one down, and one strange quark form a lambda. A quark-antiquark combination produces a particle of the meson group.

Although quarks have yet to be isolated in the laboratory (the strong force may bind them so tightly that isolation is impossible), recent evidence suggests that two more kinds of quarks exist. Their proposed names: "truth" and "beauty." Until such quarks are actually isolated, however, modern physics may take comfort in St. Paul's Epistle to the Hebrews: "Through faith we understand that the worlds were framed by the word of God, so that things which are seen were not made of things which do appear."

off and on as often as 30 times per second. Called *pulsars*, these signals are probably emitted by rotating neutron stars.

By using radiotelescopes in combination, moreover, it is possible to determine the precise location of a radio source in space through a procedure similar to "triangulation" used in navigation on Earth. Such cooperative activity enabled astronomers to detect and describe the first *quasars*—essentially radio signals from "quasi-stellar" objects with large *red shifts*. Red shift refers to the displacement of light toward the red end of the spectrum; it is approximately proportional to the velocity of a star or other stellar object as it recedes from Earth.

Another advance in astronomy has been the development of a more sensitive means of measuring light. Until recently the

ONE MAN'S REVOLUTION

Notions of how old scientific theories give way to new tend to be shaped not by scientists but by historians and philosophers of science. What is still probably the most generally held opinion among both scientists and the public is one that was shaped during the 1930s and 1940s by the school of positivist philosophers known as the Vienna Circle.

According to this view, science is a strictly logical process. Scientists propose theories on the basis of inductive logic, and confirm or refute them by experimental tests. When old theories fail, new theories are proposed and adopted because of their greater explanatory power, and science thus moves ever closer to the truth.

Logical empiricism, as this view is called, still has its defenders, but many philosophers and historians of science now favor perceptions of the scientific enterprise that take human factors into account as well as the purely logical structure.

Perhaps the principal force behind this change was a book published 16 years ago that cut blithely across the demarcation lines between the philosophy, history, and sociology of science. *The Structure of Scientific Revolutions* is a landmark in intellectual history that has attracted attention far beyond its own immediate field.

Thomas S. Kuhn, its author, was trained as a solid-state physicist but works as a historian at Princeton and the Institute for Advanced Study. His book still evokes a set of reactions that defies any general consensus. Common among science historians is the view that it is both brilliant and refutable.

"My own attitude toward the book," says one scholar, "is the same as toward a number of other books, that they are classics in the sense that they have been completely disproved in detail by the professionals in the field and yet they somehow survive."

Kuhn's thesis, in rough outline, goes as follows. Science is not the steady, cumulative acquisition of knowledge that is portrayed in the textbooks. Rather, it is a series of peaceful interludes punctuated by intellectually violent revolutions. During the interludes, scientists are guided by a set of theories, standards, and methods that Kuhn refers to as a "paradigm."

ability of telescopes to make out dim and distant objects was limited by a faint, ever-present glow throughout the sky. (Even when the telescope is pointed to areas where there are no stars, a photographic plate receives some light.) Using electronic detectors, astronomers can reduce this airglow effect almost as easily as adjusting a car's rearview mirror for night driving. They can

The paradigm is the basis of the research tradition; it defines which problems are interesting and which are irrelevant. During the paradigm-governed interludes, called periods of "normal science" by Kuhn, scientists essentially solve puzzles generated by the paradigm. Study of mechanics after Newton's *Principia* is one example of a period of normal science; astronomy after Copernicus is another.

But the tranquility of normal science does not last. Sooner or later, scientists trying to extend the paradigm find that there are puzzles they cannot solve. The time comes when these puzzles can be ignored no longer. Then the field enters into crisis, such as befell the phlogiston theory before the understanding of oxygen.

At this point, a new paradigm may be proposed, its underlying discoveries almost always being made, Kuhn states, by men who are "either very young or very new to the field whose paradigm they change." But defenders of the old paradigm patch it up with ad hoc fixes, and the battle is joined.

The means by which this battle is waged is central to the thesis because in Kuhn's view, nonrational factors play an essential role. Logic and experiment, says Kuhn, are not sufficient: "The competition between paradigms is not the sort of battle that can be resolved by proofs." In fact the transfer of allegiance from one paradigm to another "is a conversion experience that cannot be forced."

Nor can a new paradigm build on the one it succeeds; it can only supplant it. Science is not the cumulative process portrayed in the textbooks; it is a succession of revolutions, in each of which one conceptual world view is replaced by another. But Kuhn sees no ground for believing that the new paradigm gives a better understanding of the world than did the old. We may, says Kuhn, "have to relinquish the notion, explicit or implicit, that changes of paradigm carry scientists and those who learn from them closer and closer to the truth."

Since Kuhn does not permit truth to be a criterion of scientific theories, he would presumably not claim his own theory to be true. But if causing a revolution is the hallmark of a superior paradigm, *The Structure of Scientific Revolutions* has been a resounding success.

—*Nicholas Wade* © *1977* Science

now view objects so distant that the light that reaches us began its journey 10 billion years ago. The vistas opened by such research are truly cosmic: the detection of events at the far reaches of the universe, of events at the beginning of time, the creation and evolution of galaxies, the birth and death of stars.

In another direction, scientists have begun to peer deeper into "inner space"—the human body. Genetics continues to puzzle researchers, but there has been some progress. The function of chromosomal DNA as the informational material for heredity has been established. We know the gross structure of DNA, including the pairing of DNA strands portrayed in the famous Watson-Crick double helix. But scientists still don't know what turns a gene "on" and "off." That is, what processes direct genes toward that complex series of steps that culminates in a new organism?

One way to find out is to isolate specific genes and work with them in test tubes. The best way to prepare these genes involves what is popularly known as "gene-splicing," a method based on the 1972 discovery of *restriction enzymes.* These enzymes, of which about 30 are known, split DNA in highly specific ways. Afterwards, one strand of the DNA protrudes beyond the other. The two pieces of the chromosome can be rejoined by what amounts to splicing.

Insoluble Puzzles?

Alternatively, two *different* chromosomes can be split, and then part of one can be spliced onto part of the other to create an entirely new form of DNA. This "recombinant" DNA can be introduced into bacteria; there, biological machinery will produce more of the DNA along with what, for the bacteria, are novel protein products.*

The deepest mysteries in the biomedical sciences surround the workings of the brain. People knew thousands of years ago that extracts from the opium poppy could relieve pain, ease anxiety, produce euphoria, or help bring sleep. During the past five years, scientists have discovered that the human nervous system makes its own opiates, different chemically from those of the poppy but producing similar effects. These substances were found to be *pentapeptides* (compounds formed by the union of five amino acids), and it was a simple matter to improve on nature by synthesizing a variant 50 times more powerful than morphine. Whatever their ultimate therapeutic value, the brain's own opiates may provide a tool for studying the nerve pathways responsible for pain, emotion—even for the thrill of discovery.

The scientific method is most effective, of course, when a

*Concerned about the consequences of such work, the National Institutes of Health in 1976 published guidelines governing recombinant DNA research. The rules provide for separation of altered organisms and require that research take place only on organisms incapable of life outside the laboratory.

problem can be separated into simple, solvable parts. Some biological phenomena are extremely complex; others are virtually inaccessible to observation. One goal that is likely to be approached only slowly for these reasons is control of cancer, which is not one disease but hundreds. Another is genetic engineering; complex ties among the biological systems that control growth guarantee that even minor tinkering remains distant, though not unrealistic. Far less probable is the much-publicized "cloning" of human beings or the extension of our life span much beyond the Biblical three-score-and-ten. Events will surely demonstrate that the answers to some questions are beyond human ingenuity.

Our visitor from 1928 would certainly recognize that problem. He would recognize other things as well, notably that the basic nature of scientific inquiry remains essentially what it was a half-century ago. It is hard work. When new ideas and insights occur, they come from individuals. In general they come from a person who has been immersed in a problem (like Archimedes in his bath when he shouted "Eureka!") and who has wrestled with a set of frustrating puzzles and contradictions until a light dawned.

The individual scientist's quest is still largely driven by the human desire to be the first to explore, the first to reach a new plateau of knowledge. Scientists will endure long periods of struggle and disappointment to enjoy the sudden pleasure of a new insight—followed by the reward of professional acclaim and, more rarely, a Nobel Prize. Do these motives seem impure? Perhaps they are. But the motives will be forgotten; the legacy to science will not.

DILEMMAS DOWN THE ROAD

by John D. Holmfeld

Since World War II science has become a major claimant on the federal budget; it now involves every federal department, some 45 congressional committees, a score of specialized agencies, about 500 universities, and nearly 2 million scientists, engineers, and technicians—one third of them concentrated in research and development.

If this effort seems diffuse, there are nevertheless some overarching principles. Among them: that the federal government should, in fact, be in the business of supporting science, and that a substantial share of that support should go to the universities. This essentially political consensus underlies the growth of modern American science.

Often forgotten is the fact that the policy of federal support for science in general—and for the universities in particular—is less than four decades old. Like Keynesian economics, which served as a basis for U.S. government economic policy for 40 years until the "stagflation" of the 1970s, some of the general assumptions of federal science policy are now being challenged.

The public and private universities face severe enrollment declines in the 1980s; their scientific endeavors have already been weakened by inflation, and obsolete instruments and facilities have not been replaced. "There is no doubt," reports Charles Kidd of the Association of American Universities, "that academic science has decayed in recent years." Not yet by much, to be sure, but the trends are clear.

Meanwhile, congressmen and agency officials worry about the magnitude and direction of the larger research effort. Should the current diverse pattern of federal subsidies be somehow reshaped to funnel scientists into specific tasks? Recently there have been sizable increases in government outlays for energy and environmental research. At the same time, funds for basic research, which rose by 11 percent annually during the 1960s, are now increasing at a yearly rate of only 5 percent, thereby encouraging "basic" scientists to go into "applied" fields. Should these trends be further encouraged by Washington? "If we push too far one way," warned Senator Edward Kennedy (D.-Mass.), chairman of the Senate Subcommittee on Health, "it could mean loss of cherished scientific freedom; but if we push too far the other way, it could mean investing billions of public dollars on research that remains irrelevant to fundamental human needs."

One of the government's justifications for its support of scientific research is that an advanced society has an obligation, for inspirational or cultural reasons, to maintain the arts and sciences. There is continuing popular interest in such fields as astronomy, oceanography, and physics. Although no one can define what the "right" level of support for science as a cultural activity should be, it is surely exceeded by the present level. In fact, the current level can only be justified in terms of an eventual technological benefit to society.

The Reservoir of Research

The use of tax revenues to pay for scientific research stems from a dramatic change that took place during and immediately after World War II. Prior to that time, the government had fostered little research except in applied fields such as agriculture or in the "mission-related" activities of the U.S. Coast and Geodetic Survey and other agencies. During the 1920s and '30s, basic research was generally viewed by Washington and the public as the province of the lone, even eccentric scientist—of people like Albert Einstein, whose work in relativity and atomic physics was expected to have little practical benefit. Then came World War II, radar, the proximity fuse, mass-produced penicillin, and the atomic bomb, all growing out of the earlier "impractical" work of generally unknown American scientists.

As a result, the pendulum in the postwar years swung to the opposite extreme, with basic science seen as the key to national security, technological progress, and public health. The cost of this shift was cheerfully borne by Washington. As Vannevar Bush put it in his influential *Science: The Endless Frontier* (1945), "We can no longer count on ravaged Europe as a source of fundamental knowledge." Bush, the Yankee engineer and M.I.T. dean who became President Roosevelt's science adviser, stressed the urgency of replenishing the reservoir of research findings so that society could tap the results for their technological applications. Not all of it would be tapped immediately, he conceded, but most of it would be tapped eventually, even if it was impossible to say exactly when and where.

With this rationale—prodded further by Sputnik and competition with the Kremlin—Washington embarked on a spectacular expansion of scientific support. From the modest sum of $74 million in 1940, federal science outlays have grown steadily. Last year $14.2 billion was spent in the United States on scientific research, of which $8.1 billion came from federal sources. Some $14.4 billion of the $40.8 billion invested in technological development also came from the government.

To disburse these vast sums there emerged an array of federal agencies: the Atomic Energy Commission (1946), the National Science Foundation (1950), the National Aeronautics and Space Administration (1958), and several others. The investment yielded great advances in medicine, physics, space, oceanography, and indeed in every scientific field.

Questioning Dr. Bush's Rationale

In recent years, however, the pendulum has begun to swing back once again—the result of no single issue but of a pervasive sense on Capitol Hill and among the public that our money could be better spent.* In the popular press this is reflected in "horror stories" suggesting frivolous government expenditures on such subjects as "Polynesian Linguistics" or "Basic Labor Productivity Measures for Popular Breakfast Menu Items." But more serious expressions of concern have also been heard.

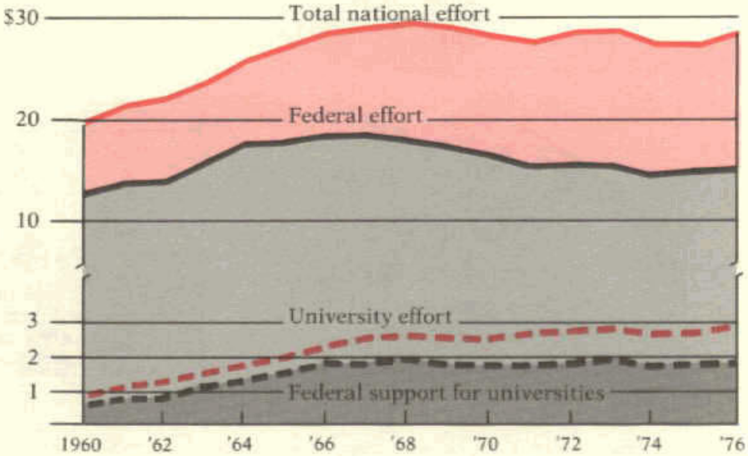
Some observers doubt that much current research will ever prove useful. Others wonder if basic scientific research will really provide the "best" solution to certain problems. These are not always simply "antiscience" questions; they are not aimed at getting government out of the laboratory. But they do suggest that there may be better ways to allocate science money.

The idea that most scientific research eventually finds a use

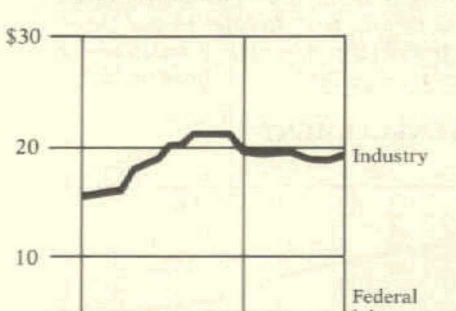
*One early manifestation was the Mansfield Amendment to the 1970 Military Appropriations Act. The amendment prohibited the use of defense funds for research that lacked "a direct and apparent relationship to a specific military function." Though no longer in effect, it has had a lasting—and inhibiting—effect on the Defense Department's basic research effort.

John D. Holmfeld, 48, is a staff member of the House Committee on Science and Technology with responsibility for science policy. He received a B.S. in engineering from M.I.T. (1957) and earned a Ph.D. in science, technology, and public policy from Case Western Reserve University (1969). The views expressed here do not necessarily reflect those of the Committee on Science and Technology.

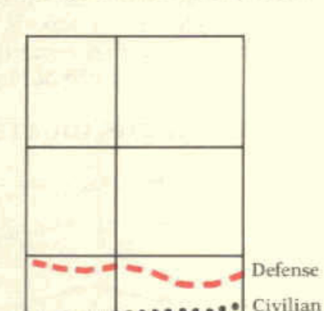
FINANCIAL SUPPORT FOR RESEARCH AND DEVELOPMENT
(in billions of constant 1972 dollars)



R&D 'Performers' *



Federal R&D Obligations

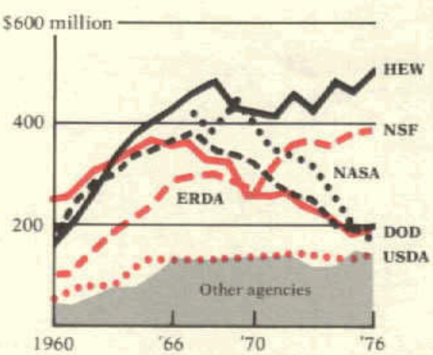


Since 1967, total R&D support has slipped 3 percent, with the federal share down by 18 percent (top). The mix of major R&D performers is unchanged (above, left) but the emphases in federally funded research have changed substantially (above, right). Defense and space R&D are down 18 and 50 percent, respectively; civilian R&D, swollen by energy and environmental research, is up 48 percent.

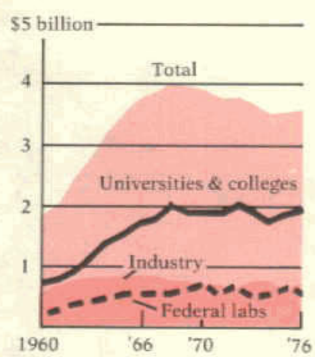
*Excluding federally funded R&D centers and miscellaneous nonprofit research institutes.

BASIC RESEARCH (in constant 1972 dollars)

Federal Obligations by Agency*



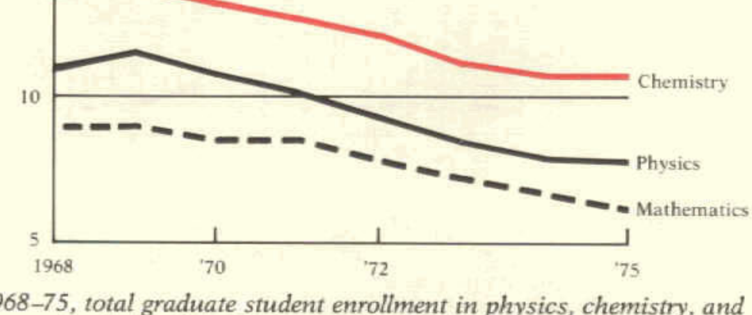
Expenditures by Performer†



*U.S. Department of Health, Education, and Welfare; National Science Foundation; National Aeronautics and Space Administration; Energy Research and Development Agency (Atomic Energy Commission, prior to 1974); Department of Defense; Department of Agriculture.
†Excluding federally funded R&D centers and miscellaneous nonprofit research institutes.

Dramatic shifts have occurred in federal agencies' basic research funding, with HEW and NSF reaching new highs but all others dropping below earlier peak levels (above, left). Sharpest decline: in the Defense Department. Universities remain the chief performers of basic research (above, right) but their 1976 outlays are 4 percent below those of 1972.

FULL-TIME GRADUATE ENROLLMENT



In 1968–75, total graduate student enrollment in physics, chemistry, and mathematics declined by 30, 21, and 31 percent respectively. First-year enrollments have since picked up slightly in physics and chemistry.

Charts adapted from The State of Academic Science *(New Rochelle, N.Y.: Change Magazine Press, 1977) and* Science Indicators 1976.

was explored by a House subcommittee in 1976. It concluded that although we have an accurate picture of the resources going into the $22 billion federally supported R&D system, "in terms of what, so to speak, comes out the other end of the pipeline, little of a quantitative nature is available." Individual success stories—penicillin, transistors, the ball-point pen—have long served to justify the government's investment. These anecdotes, as one congressman noted, "are of undoubted veracity but of unknown representativeness." In terms of the Bush rationale, the question is whether a large percentage of scientific research placed in the common reservoir of knowledge ever emerges again. Even granting that many findings will contribute to technology indirectly through further advances in basic science, government officials wonder how many studies and papers sink to the bottom of the reservoir without a trace.

A second concern is that basic research may not provide the most effective solution to some major problems. This is especially apparent in the largest government-supported field, biomedical research, long a congressional favorite. Funded chiefly through the U.S. National Institutes of Health, a great deal of biomedical research is based on the notion that once a disease is understood, a cure is near at hand. Proponents of basic research point out that this approach has often been successful, and they note, anecdotally, that if efforts to deal with polio had been concentrated on the development of better iron lungs, progress would have been modest indeed.

Troubled Universities

In cancer research, it is becoming clear that this strategy is, at least for the short term, less effective. Here, prevention—the elimination of carcinogens from our food and environment—would probably save *more* people *sooner* than an eventual cure based on research into the nature of cancer. "We have wiped out smallpox, we have wiped out cholera and typhoid and typhus," one scientist reminded a congressional panel. "We don't know very much about how these diseases are caused, but what we do know is how to prevent them, and that can be something very different."

An alternative strategy would reduce reliance on basic research as the means of solving such problems. At issue is not the value of scientific research per se, but the magnitude of the effort and the need to be selective in the use of the government's money. It is too early to say how—or if—this dilemma will be resolved. But any modifications will certainly affect the current precarious position of the great research universities, nearly half of whose 150,000 scientists and engineers are working on federally funded research projects with a combined budget of $2.5 billion.

The universities are plagued by problems they can do little about. Enrollments will decline by about 15 percent in the 1980s because the 1950s baby boom is over; the dollar will decline because inflation persists. Universities have already been forced into cutbacks to avoid or eliminate deficits. Graduate enrollments have dropped sharply in physics, mathematics, engineering, and to a lesser extent, chemistry.

These factors have reduced the ability of universities to hire young scientists fresh from their Ph.D. studies. This is the age group that most frequently makes the path-breaking discoveries (physicist Carl Anderson, for example, discovered the positron two years after earning his Ph.D.; he was 27). Now, science departments are overtenured (as high as 70 percent in some fields), and positions may have to be eliminated when the demand for graduate training drops.

Where To Invest?

There is no lack of proposed remedies. Students as well as the federal and state governments are being asked to contribute more to defray the cost of research and education—the latter already subsidized by "overhead" payments on research grants awarded to the universities. There is also pressure within the federal government for subsidies of general university operating costs—a course Congress has hitherto avoided. And Dr. Frank Press, now President Carter's science adviser, urged in 1975 that the traditional close association of teaching and research in the universities be weakened. Young scientists could then be hired not to teach but to do research exclusively in federally sponsored research centers within the universities. Whatever the proposals, the message is clear: both Washington and the research universities are worried about the future.

Basic to the debate is the question of whether the government should continue to invest so heavily in the universities in order to maintain this unique source of research; or whether it should instead place a greater share of its research funds in the hands of, say, industry, or perhaps entirely new types of institutions. In his 1945 report Vannevar Bush had touted the universities as "uniquely qualified" to carry on basic research. Since that time the government-university relationship has come to seem indispensable—and undissoluble. Frank Press observed several years ago that the strength of U.S. science was "directly related to the health of the universities." But Press and others have noted that in its reliance on these institutions, the United States is unique. Other countries employ a more diverse group of institutions. Germany's Max Planck Institutes, which perform specialized research in medicine, chemistry, and physics with government funds, are often cited as an example.

Several recent proposals would shift some research responsibility away from the universities. The most notable was that of the Senate Committee on Labor and Public Welfare, which has jurisdiction over the National Science Foundation. Pointing out that an increasing number of bright, young scientists were finding employment not in the university but in industry, the committee last year urged an end to NSF's preferential treatment of academic scientists. This proposal was not enacted into law.

However the matter is resolved, the government, looking to the future, must consider how society's needs will be served. University officials often describe the current labyrinthine funding arrangement—with its many sources of money in many different agencies—as a healthy kind of "pluralism." Looking in the direction of research "performers," the government may find pluralism healthy, too.

Less than 40 years ago the science-government relationship underwent a radical change. It may be on the verge of changing once again, as the principle of government support of science —mainly in the universities—comes under increased scrutiny. Even if it does change, we should not forget the resilience of American science, which moved from obscurity to the front rank in scarcely two generations.

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BACKGROUND BOOKS

SCIENCE IN AMERICA

The scientists known to the American public today are not inventors like Thomas Edison, Alexander Graham Bell, and the others who became famous in the 19th century for technological innovations. Nor are they discoverers of new principles, like the 20th century's Albert Einstein. They are not leaders of the scientific community who have served as spokesmen in high places—such as Nobel Prize–winning physicist Robert Millikan after World War I and electrical engineer Vannevar Bush after World War II.

In the view of Rae Goodell, today's best-known scientists are those who pop up repeatedly in the media, aggressively seeking "to influence people and policy on science-related subjects—overpopulation, drugs, genetic engineering, nuclear power, pollution, genetics and IQ, food shortages, energy shortages, arms control."

In **The Visible Scientists** (Little, Brown, 1977), Goodell, assistant professor at M.I.T., names seven such scientists recognized largely for their public involvement: Paul Erlich, lepidopterist, who has been trying to halt the population explosion; Nobel chemist Linus Pauling, tireless both as promoter of vitamin C to prevent colds and as agitator for disarmament and world peace; Margaret Mead, for "50 years the people's anthropologist," who has moved from Samoan sexual customs to the "generation gap" to concern for the environment; B. F. Skinner, the "determinist" psychologist, now writing "a behavioral interpretation of my life as a behaviorist"; Carl Sagan, the "Pied Piper of astronomy, captivating youngsters and taxpayers with his 'cosmic overwhelm'"; botanist Barry Commoner, "the Paul Revere of ecology," who has propagandized the public with his books and articles; and Nobel physicist-turned-geneticist William Shockley, whose extreme views on the links between race and intelligence have made him a highly controversial figure.

Less publicized have been the scores of leading scientists who have worked in the laboratories and pushed for private and federal support over the years. The complex story of American science has many threads.

Daniel J. Kevles brings the strands together for one branch of science in his highly readable work, **The Physicists: The History of a Scientific Community in Modern America** (Knopf, 1978).

As Kevles follows physics from its beginnings as a minor element in the "natural philosophy" curriculum in American colleges before the Civil War to its present cosmic eminence, he also chronicles the evolution of federal subsidies for physics. Greatly enlarged for atomic research during World War II ("A Physicist's War," Kevles calls it), the funds available for physics have not continued to expand at anything like the rate of new discoveries in, for example, high energy "particle" physics. Although 6 of 11 Nobel Prizes in physics since 1965 have been won or shared by Americans, federal outlays for basic physics in 1977 totaled less, allowing for inflation, than they did in the Johnson years a decade earlier.

Charles Rosenberg, University of Pennsylvania historian, gives a good sense of how and why other sciences, including biology, medicine, and agronomy, have fared differently in attracting the public's interest and government research money. His essays are collected in **No Other Gods: On Science and American Social Thought** (Johns Hopkins, 1976, cloth; 1978, paper).

For an understanding of the early days of geology in the United States, the book to read is **Exploration and Empire: The Explorer and the Scientist in the Winning of the American West** (Knopf, 1966, cloth; Norton, 1978, paper). Pulitzer Prize–winner William Goetzmann describes the adventures of U.S. Geological Survey employees and other geologists working on their own or for the mining industry as they pushed the U.S. frontier to the Pacific Ocean. Scientific artists preserved a vivid record of what the explorers found as they moved into the mountains and desert canyons beyond the Mississippi in panoramic paintings, topographical maps, cross-sections of such wonders as the Grand Canyon, and biological and zoological drawings. A portfolio of their work is included in Goetzmann's book.

The beginnings of American science's institutional story are told in **The Pursuit of Knowledge in the Early American Republic: American Scientific and Learned Societies from Colonial Times to the Civil War** (Johns Hopkins, 1976). This collection of papers edited by Alexandra Oleson and Sanborn C. Brown describes the establishment of the Royal Society in America, the Philadelphia Academy of Natural Sciences, the Franklin Institute, and other important early centers for the promotion of the sciences from astronomy and botany to zoology.

One of the contributors to the Oleson and Brown book, Sally G. Kohlstedt, has written her own early history (1849–60) of the American Association for the Advancement of Science; **The Formation of the American Scientific Community** (Univ. of Illinois, 1976). She records the efforts of scientists in several fields to disentangle themselves from well-meaning amateurs and establish professional science on a firm footing.

In **Dollars for Research: Science and Its Patrons in Nineteenth-Century America** (Univ. of Washington, 1970), Howard S. Miller analyzes the growth of private subsidies for research in many fields. He credits U.S. Coast Survey Superintendent Alexander Dallas Bache (1806–67) with giving private support of science its early impetus. Legislators lacked scientific understanding and often bungled public appropriations. Private agencies like Boston's Lowell Institute, Bache thought, were wrong in only offering "a bounty for good lectures; we want a bounty for research."

With physicist Joseph Henry, Harvard mathematician Benjamin Peirce and astronomer Benjamin A. Gould, chemists Oliver Wolcott Gibbs and John F. Frazer, Swiss-American zoologist Louis Agassiz, and other occasional members, he formed "The Order of the Scientific Lazzaroni" (named after the poorest class of Neopolitan beggars) to marshal support for research. In 1846, when the Smithsonian Institution was established, Bache became its youngest regent.

An analogue to Miller's history of the private sector's investment in research is A. Hunter Dupree's classic (but out-of-print) **Science in the Federal Government: A History of**

Policies and Activities to 1940 (Harvard, 1957; Harper, 1964). Dupree takes the chronicle of Washington's fitful disbursement of taxpayers' money to scientists up to World War II. His principal interest, however, is in federal science policymaking and how it evolved.

Several practicing scientists extend that policy story from the end of the war through the Sputnik era. One of them, Vannevar Bush, actually *made* policy with the publication in 1945 of **Science: The Endless Frontier: Report to the President on a Program for Scientific Research.** Bush was then director of the U.S. Office of Scientific Research and Development. His historic report was reissued by the National Science Foundation in 1960 but is no longer available outside libraries. Following Bush's recommendations, information on wartime discoveries was released to private industry; the National Science Foundation was established (1950) following the consolidation and expansion of the National Institutes of Health (1948); and a series of new federally supported programs in basic sciences were begun in U.S. high schools, colleges, and universities.

Recent books by later top-level advisers are **Sputnik, Scientists, and Eisenhower: A Memoir of the First Special Assistant to the President for Science and Technology** by James R. Killian, Jr. (M.I.T., 1977) and **A Scientist at the White House: The Private Diary of President Eisenhower's Special Assistant for Science and Technology** by George B. Kistiakowsky (Harvard, 1976).

Killian, who had been president of M.I.T. before his appointment, was succeeded by Kistiakowsky, a Harvard professor who had been part of the Los Alamos team; the two men did not always see eye to eye with each other or with the President and Cabinet members. Their memoirs are eloquent on the problems that arise in the marriage of science and politics, including a severe language barrier.

Two excellent narratives that explore the broad implications for Americans of government participation in science, and vice versa, are **The Scientific Estate** by Don K. Price (Harvard, 1965) and Daniel S. Greenberg's **The Politics of Pure Science** (New American Library, 1967). Price, recently retired as head of the Kennedy School of Government at Harvard, is the much-admired dean of academic analysts of the relationship between science and politics. Greenberg has long been accorded similar esteem among lay science writers.

Price observes that the 1945 Bush report "reversed the traditional policy of the United States in two ways" by persuading universities and private research institutions that they had to ask the government for financial aid and by persuading the government that basic science, as well as applied research, deserved support. But, "Hardly anyone stopped to ask the fundamental question: How is science, with all its new power, to be related to our political purposes and values, and to our economic and constitutional system?"

Lawrence R. Veysey, in his fine historical study **The Emergence of the American University** (Univ. of Chicago, 1965), notes that "'pure scientists' had a great deal to do with the university's development in the late 19th century." And as science shaped the schools, so have the schools shaped American science, Dael Wolfe shows in **The Home of Science: The Role of the University**

(McGraw-Hill, 1972).

The colleges and the government today share the problem of determining research priorities. Both also have a role in safeguarding the public from possible, or proven, harmful side effects of laboratory experimentation.

Recent work in genetics has produced the latest surge of uneasiness. A definitive but rather difficult book about discoveries in this field since German medical researcher Friedrich Miescher's 1869 identification of DNA (he called it nuclein) is **A Century of DNA: A History of the Discovery of the Structure and Function of the Genetic Substance** by Franklin H. Portugal and Jack S. Cohen (M.I.T., 1977).

Less detailed but more than enough for most lay readers is Nicholas Wade's **The Ultimate Experiment: Man-Made Evolution** (Walker, 1977). Wade assesses the possible dangers—especially that of epidemics of new diseases—from current recombinant DNA experiments ("gene-splicing"), in which new forms of cellular life are created. He considers the laboratory controls on them effective, at present.

James P. Watson's **The Double Helix: Being a Personal Account of the Discovery of the Structure of DNA** (New American Library, 1969, paper; Atheneum, 1977, cloth & paper) conveys the excitement of a scientist on the track of something new and startling. The author now heads an important biological laboratory at Cold Spring Harbor, New York. In 1962 he shared the Nobel award for medicine and physiology with his Cambridge University associate Francis Crick and their rival in a research race that came to a close finish, Maurice Wilkins of King's College, London. Engagingly uninhibited, Watson frankly reveals the tensions among researchers working independently toward the same goal. The Englishmen were nonetheless friendly competitors; all hoped to beat out (as they did) Linus Pauling, who was also working on the molecular structure of deoxyribonucleic acid, in California.

One behind-the-scenes rivalry barely hinted at in Watson's book has become a *cause célèbre* for the women's movement. It is the subject of Anne Sayre's **Rosalind Franklin & DNA** (Norton, 1975, cloth; 1978, paper). Franklin, who died in 1958, was a member of the King's College team working alongside Wilkins on DNA. Many geneticists today believe that her work provided the key to the final unraveling of the DNA mystery. But by the time the Nobel committee met, she was forgotten. Sayre's rehabilitation of the King's College laboratory assistant whom Watson calls "Rosy" in his book and consistently puts down ("the best home for a feminist is in another person's lab") is somewhat emotional. But it deserves to be read along with Watson's exuberant account by anyone interested in discerning the true path to the double helix.

EDITOR'S NOTE. *Many scholars of science contributed suggestions for this essay, particularly Nathan Reingold and John Holmfeld. Other ideas or specific titles were recommended by Wilson Center Fellow Ingemar Dörfer, by long-time* Science *magazine staffer John Walsh, and by Winfield Swanson, a medical science writer.*

Inspired in the 1950s by the work of France's Marcel Duchamp (Mona Lisa with moustache), "pop art" is a major movement in modern painting. The subjects chosen by such American artists as Andy Warhol (Campbell's Soup can, Coke bottles) and Roy Lichtenstein (sneakers, lettering) show pop art to be the opposite of popular culture. Pop culture deals in the mass production of "legitimate" artistic genres; pop art takes mass-produced, everyday objects and turns them into "originals."