New technology for science: Where will it come from?

Furthering scientific excellence at all levels is a Federal mission; like other missions it deserves support for fundamental engineering research.

Lewis M. Branscomb

This is a watershed time in the relationship of American science and engineering to the nation's future, for many circumstances have changed since basic US science policy was set in the 1950s. More than ever, the cornerstone of our science policy must be a national commitment to excellence in both science and engineering.

Scientific and technological achievement, like entrepreneurial skill and athletic prowess, are important elements of American culture. We measure the vitality of our society by our attainments in all these areas, just as we measure the quality of our society by the prevalence of justice, equality and caring. But scientific and technological achievement is also a means to a broad variety of very important ends. Thus a national science policy must focus not only on strengthening science but on the processes through which a strong science will benefit current and future generations of Americans.

This is precisely why generating a consensus on national science policy is so difficult. Almost everyone can agree on the importance of world leadership in basic science; it is much harder to agree on national policies to improve the effectiveness of the mechanisms that harvest the fruits of science. An unintended byproduct is that our scientists are left to make the best progress they can without the supporting infrastructure that could accelerate scientific progress and at the same time invigorate our technology.

The changing nature of science

The practice of science and engineering is profoundly changing, blurring the distinction between them and enormously increasing their power for progress and for application. But this change comes at the cost of increasing complexity and intensive use of capital, putting great pressure on scientific institutions.

Individual creativity remains the keystone to excellence, but scientific leadership increasingly depends on systems and software science, on pandisciplinary approaches, on sophisticated, intelligent instrumentation and on new information networks. Developing these tools requires technological support beyond the skill of even the most gifted "love, string and sealing wax" physicist.

Today, as we in industry keep pushing our technology beyond conventional practice in the quest for higher performance and lower costs, our dependence on leading-edge science grows increasingly acute. Engineering has changed as much as science. It is no longer a "handbook" profession, but must work with the still undigested primary literature of science.

By the same token, modern science owes an increasing debt to the latest in technology, which provides the tools needed by an ever more sophisticated science. We may think of chemistry as "small science," but a scanning electron microscope, a Fourier infrared spectrometer, a big chromatograph and a scanning tunneling microscope—all of which are now basic tools—can cost hundreds of thousands of dollars apiece.

We have understood the importance of the scientific basis for technology for many years; now we must also invest in the technological basis for doing and using science. The result could be to reinvigorate engineering as well as to stimulate science.

The new policy on engineering worked out by the National Science Board during the last five years is of great potential importance and yet it is only a small first step. The nation's universities are eager to respond, as indicated by the $2 billion in proposals submitted for new NSF Engineering Research Centers—six of which are being funded during fiscal 1985, at a total cost of about $9.5 million. But the

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0031-9228 / 86 / 0200 35- 05 / $01.00

Magnet facility at Fermilab. The photo shows the 4.5-T dipole magnets for the Tevatron being assembled. Generating this field strength required the solution of exacting engineering problems, such as the manufacture of coils of the required mechanical rigidity and the development of Nb–Ti superconducting cable suited for a high critical current density. The success of these magnets opened the way for the choice of a similar design, operating at 6.4 T, for the Superconducting Super Collider.

Administration and Congress have not yet faced up to the implication of supporting the kind of technology base our universities should be providing.

Focus on technology for science

Science policy, I suggest, should explicitly focus on funding for the technology that is needed to move science ahead, on the grounds that this is good not only for science but also for engineering.

Traditionally, American policy has always been to fund the basic research and let the scientists figure out where they're going to get their technology. Exceptions to that have been national laboratories that have developed huge, expensive facilities, such as the Space Telescope and the Tevatron, where very aggressive, original engineering and science are done together in the same project to create a capability that didn't exist before—advancing engineering and producing exciting science at the same time.

Yet even here, most of these national laboratories have not been given the mission of supporting the technological base on which their future capabilities rest. Rather, they have invented their way around the limitations of today's state of the art in technology. A similar strategy ought to underlie a much larger fraction of our total US science program than it does today. And we should begin to move beyond this point toward well-considered exploratory development of new technology for future science.

What I am suggesting is nothing less than accepting that scientific excellence *is* a Federal mission and that NSF and NIH, like the Energy Department's research program, *are* "mission-oriented" agencies. The mission of DOE research is more than the development of future energy resources; it is progress in the underlying science and manpower base as well. When this approach is accepted in other agencies, we will have resolved the 30-year debate on how to keep the missions of our national laboratories fresh, challenging and important.

One reason NSF, for example, has invested comparatively little in the frontiers of engineering is that it has traditionally used the quality of the science it funds as the sole measure of merit. The quality of the supporting engineering is given little weight. Nor has the NSF engineering program been willing to undertake strategic support for engineering innovations in support of scientific objectives, in spite of the high priority the nation places on them.

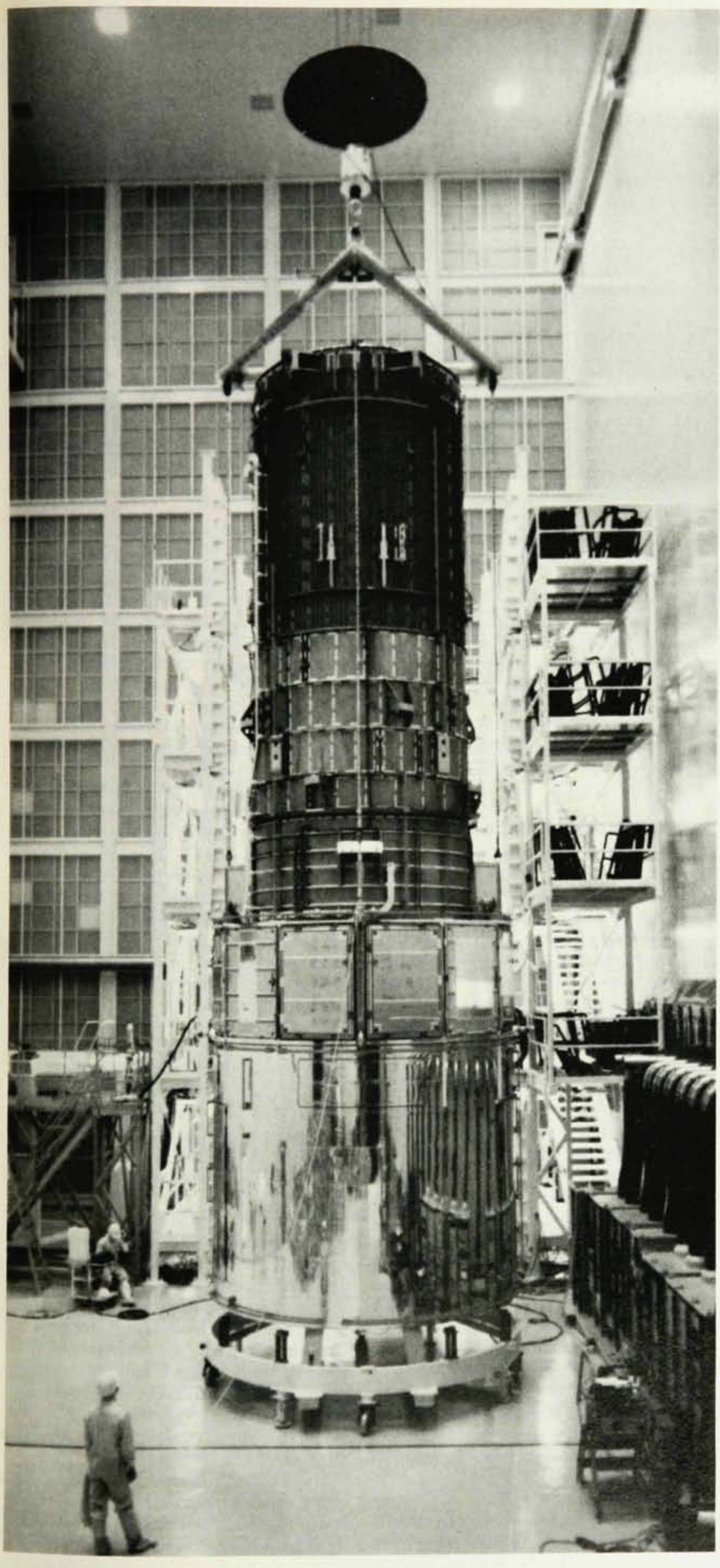
Let me illustrate the fallacy of the traditional NSF policy with the US Antarctic Research Program, in which the science is excellent but some of the supporting engineering leaves much to be desired. The reason is that Antarctic research is run totally as a scientific program, with little investment in technology to make the whole program more efficient. Granted, some of the tried and true, older technology in Antarctica works very well indeed. Having been there twice, I can vouch for the marvelous things our Navy pilots do with their 25-year-old Hercules aircraft and helicopters. But in other areas, such as data collection and analysis, the capabilities are often primitive, and the telecommunications facilities are still a patchwork of *ad hoc* solutions.

In spite of 24-hour sunlight in the busy summer season, there is no solar electric power; diesel fuel for the generators is flown in at an energy cost of two or three times the cost of the fuel they burn. There is no efficient and convenient means for producing water from the ice and snow: At South Pole Station, a tractor operator spends about four hours a day scooping up snow and dumping it in a snow melter. Our oceanographers make do with rented US Coast Guard icebreakers for research ships, and there is very little automation of the various synoptic monitoring efforts under way.

Until recently, engineering technologies simply have not been paid attention to in Antarctica, in part because the program is run by fine scientists who are conserving every dollar for as much science as they can afford. In fact, however, a technologically advanced support base could release inefficiently used support manpower, which could be diverted to science.

The instrumentation crisis

Another example, much closer to home, of the need to focus more attention on technology for science is the



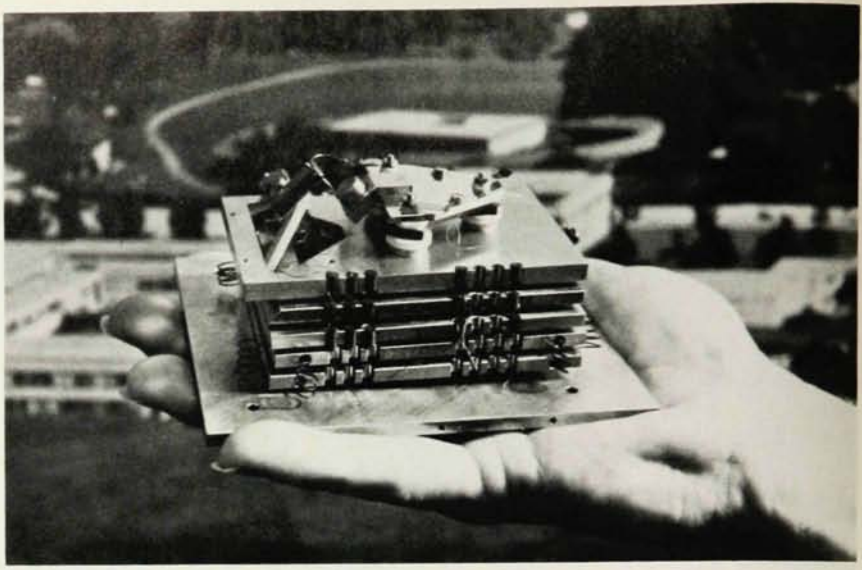
The Hubble Space Telescope, seen here at Lockheed's assembly shed in Sunnyvale, California. Its four main segments—the primary mirror, the systems and equipment section, the light shield and the aft shroud—have now been put together. Advanced technology made this instrument, a high priority for astronomers, possible.

crisis in instrumentation for small science. As the readers of PHYSICS TODAY well know, experimental science now requires much more sophisticated instrumentation than ever before. To a growing extent, instruments today *are* computers; the computer is inserted right into the apparatus itself, and the instrument becomes simply a collection of sensors serving as input and output devices on a machine that is centrally engaged in verifying a theory.

In spite of this trend, support for instrumentation is still thought of, as it always has been, in terms of money to buy commercial instruments. The funding agencies still place little or no focus on encouraging scientists and engineers at a university to collaborate in advancing the state of the art in instrumentation in any fundamental way, for the ultimate benefit of the many individual research programs that might share in the new capability.

Even if the funding agencies could get together to support such collective efforts, they are getting harder to do as instruments get more sophisticated. Time was when a single scientist could take a commercial instrument and modify its critical parts to improve it, and then a commercial company would pick up on those ideas and incorporate them into its devices. In fact that's how some of our best instrument companies made many striking product improvements. But today one may have to rewrite 50 000 lines of microcode in the instrumentation to change it.

Software technology has a vital role



Scanning tunneling microscope. The sample is visible as a small cylinder attached to the triangular plate on top of the assembly. The scanning needle hovers over the sample; voltages applied to the three legs of the piezoelectric tripod on which it is mounted serve to move the needle across the sample. A larger triangular piece of piezoelectric material mounted under the triangular plate carrying the sample is used for positioning of the sample. An assembly of springs and damping material insulates the device from vibrations.

to play in frontier science too. Computer companies, of course, compete to offer the best FORTRAN they can, the best interactive graphics programs they can and so on. At the same time university people are providing innovations in the way they use computers to do their science. But in the funding of university research, one really doesn't see a lot of concerted effort on the part of the funding agencies to encourage investigators to work on that kind of innovation.

What these agencies ought to be doing, in my opinion, is providing grants so that astronomers, say, together with software engineers could produce a set of programs for astronomical applications that would move the entire field ahead. Today it is unlikely that such a proposal would survive a peer-review committee.

Unfortunately, few people in Washington think in these terms. Scientists and engineers sometimes do, and then go off on their own to try to implement their plans. My view is that the support structure for science ought to understand the "applied" side of science as well as it understands the "basic" side. Indeed, I don't think those sides are distinguishable anymore, if in fact they ever were.

It is not the custom for NSF, anticipating spending millions on, for example, a new telescope or accelerator, to go to its Engineering Directorate and say, "Go out to the best engineers in the universities and develop prototypes of the hardware that we are going to want industry to put into this facility." And I doubt that it would occur to the Engineering Directorate to volunteer. It funds engineers to do their own thing, responding to unsolicited proposals just as the rest of NSF does. The directorate doesn't give the engineers the challenge of developing the technologies NSF requires to achieve its long-range scientific-research objectives.

I think that's too bad. Engineering, after all, is a problem-solving field. Why shouldn't the government agencies that are there to support science also support engineering in support of science? And indeed, NSF is beginning to change the way its engineering funds are expended, focusing more on problem solving related to problems of the country on a long-term basis.

Supercomputers and science

In the early years of the information-processing industry there was considerable government support for computer engineering. Indeed, the Federal government's role was very important: By stimulating the computer industry during and immediately after World War II it brought understanding of the computer's technological importance.

However, it should be understood that even in the early years it was the private corporations that largely fostered the growth of the commercial computer industry and supported the creation and early development of the semiconductor industry. In recent years the government has played a remarkably modest role in developing those technologies, even as a customer.

Today anyone not in a computer company who is seeking support for advanced research in the computer field has a choice between DARPA and NSF. The Department of Energy, for example, supports very little activity in the development of advanced computer technology. Yet the Energy Department laboratories were the ones that publicly called attention to the importance of continued US leadership in supercomputers.

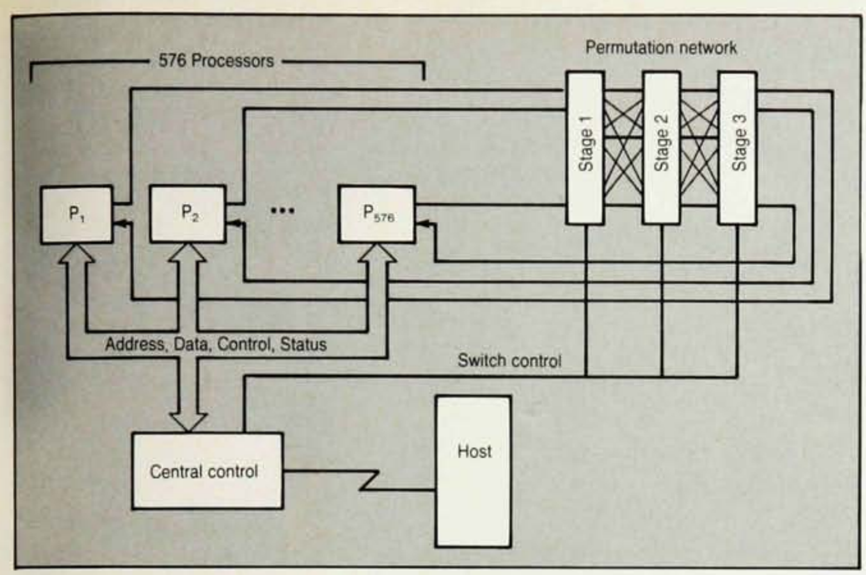
Although the jury is still out on the power of computation to transform science, clearly large-scale computing is beginning to touch science at its most fundamental level. A major change has taken place in the role of the computer in basic scientific research. Simulation is beginning to take the form of actually running a solution to a problem that is realistic from a "first principles" point of view, and mathematical theories are being proved by the "exhaustion" computational method.

There is a growing conviction that large-scale computation can be used to discover new knowledge and new principles of nature. The computer is becoming the scientist's collaborator, not just his data-reduction technician.

The field of high-energy physics in particular continues to require ever more powerful computers—not only for analysis of the data obtained in particle accelerators, but for the exploration and solution of the theoretical framework. Indeed, as planning proceeds for ever larger machines for high-energy research, such as the Superconducting Super Collider, the computational requirements for analysis and theory begin to rival the accelerators themselves in cost, complexity and importance.

Computer companies attach great importance to the computing needs of scientists and engineers, whose use of computer power is disproportionately large compared with their numbers. We also share with our colleagues in the universities the conviction that new systems designs and technologies stimulated by scientific challenges can open up exciting new possibilities for very-high-speed machines in the future.

Even though companies such as IBM can sponsor only a small fraction of the nation's basic research, we too have our Tevatron-like projects, aimed at giving



Architecture of a parallel computer, the GF11, currently under development at the IBM Thomas J. Watson Research Center. The machine incorporates 576 floating-point processors arranged in a modified single-instruction multiple-data architecture. Each processor has space for 2 megabytes of memory and is capable of 20 Mflops, giving the total machine a peak of 1.125 gigabytes of memory and a capability of 11.52 Gflops. At each machine cycle any of 1024 preselected permutations of data can be realized among the processors. The main intended application of the GF11 is a class of calculations arising from quantum chromodynamics.

a few of our research people the opportunity to stretch the art of the possible in technology to the absolute limit in the quest for dramatic scientific progress.

An example is a massively parallel experimental computer called the GF11, now under development at IBM's Thomas J. Watson Research Center. The GF11 is anything but a general-purpose machine, having been designed specifically for very lengthy quantum-chromodynamics calculations. A typical QCD mass calculation on a super-minicomputer might take 30 000 years; even on a Cray-1 supercomputer it would take 100 years. Our hope is that the GF11's 576 single-chip processors will be able to complete the same calculation in a mere year of night-and-day computing.

IBM undertakes noncommercial projects such as the GF11 to advance our knowledge of parallel processing, true, but also because they motivate our scientists and everyone else in the field to reach beyond where they thought they could reach.

A new kind of microscope

Another example of engineering for science in industry is an absolutely new kind of tool developed at IBM Research's laboratory in Zurich for examining surface structures at the atomic level with unprecedented resolution. In the scanning tunneling microscope a minute electrical current tunnels between the surface of the material under study and a probe just above it. The current rises or falls drastically if the probe approaches or pulls away from the surface, and this variation is used in a feedback mechanism to keep the probe's separation constant and trace a profile of the surface under its path. The power needed to maintain a constant tunnel current is monitored to provide a picture of the surface under study.

IBM is using STM to investigate the properties of materials important to future microelectronic circuitry, but we invested engineering effort in its development also because we thought it could be an important tool for science generally. And early on we encouraged and cooperated with universities and other industrial laboratories that wished to use, and in many cases replicate, this new instrument.

Science and technology, hand in hand

That brings me back to the idea of a national science policy that would bring science and its technological support along hand in hand. Increasingly, engineers are pursuing fields of research that are empirical, innovative and technology driven, for which no science base exists and one must be developed. Equally, science increasingly depends on new technology. These areas challenge engineers and scientists to work together.

Industry invests in unique prototype projects, such as the GF11 and the scanning tunneling microscope, for the learning value and the opportunity to make what we always hope will be a strikingly interesting contribution to science. But to augment those efforts, government agencies should equip applied scientists and engineers in universities and national laboratories with the support they need to invent and exploit new, experimental materials, technologies and systems for the pursuit of long-range research strategies aimed at advancing the frontiers of science.

Much of the technology scientists need is general-purpose technology, and they can generally obtain it from the same commercial sources everyone else does. But increasingly some of the most critical achievements in basic science require the invention of new and unique instruments and tools. Historically, basic researchers themselves invented those tools, and some with entrepreneurial talent started companies and got into the instrument business themselves. That is still one way in which newly invented tools of science diffuse into an industrial source of instruments for other researchers.

But if, for example, the Department of Energy goes ahead with its Superconducting Super Collider, the scientists cannot and should not try to do it alone; industry will have to help develop and build that huge, complex machine. Now companies can help a lot when it serves to stretch their own science and technology capabilities. But in the case of a single-use system such as SSC, one cannot reasonably expect industry to make a major investment without a partnership with government, with shared strategic objectives. Government agencies have no difficulty understanding the value of such a partnership in the pursuit of strategic defense objectives. Is scientific leadership not a national strategic objective too?

I realize that this idea may have hard going, not only with scientists who see their funding as a dwindling sliver of a fixed pie, but with engineers who might not be so enthusiastic about the scientist serving as the source of goals for technology. Nevertheless, complex systems technology is becoming the meeting ground for science and engineering. A new partnership, fostered by government, should be forged. Let it be forged under the banner of scientific as well as technological leadership.

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This article is based on a lecture delivered at the Fermi National Accelerator Laboratory on 12 April 1985. □