MEASURING WHAT COUNTS IN SCIENCE

A Speech by Bruce Alberts, President
National Academy of Sciences
Presented at the Academy's 134th Annual Meeting
April 28, 1997

I am delighted to welcome you to our 134th annual meeting. This is always a special opportunity for us to communicate. I have read all of the comments returned by the more than 1,100 members who replied to our recent survey. Each of you will be getting a summary of the results later this morning. This information is critically important to us, and it will help us improve our connections to members.

As many of you have pointed out, it is crucial that the Academy maintain a focus on our most important goals. And one of my obligations as president is to make sure that these goals are clearly articulated. One of the most important of these is to ensure that all of the advice we give to the government is independent of government or other influences, being based solely on science — not politics. Yet, as I speak, our independence is being threatened by lawsuits, as many of you are well aware. The processes that the Academy has carefully put in place for our studies — from selecting members of our committees, to subjecting each draft report to rigorous, anonymous peer review — are fundamental to our ability to provide the best science advice possible. In service to the nation, we must do all that we can to ensure that the important role that we play in helping to inform public policy is preserved.

Bruce Alberts, president, National Academy of Sciences

But in this address, I would like to go beyond the specifics of the moment, and talk about the goals and priorities of this great institution — emphasizing our responsibilities as scientists in a world that will soon enter a new century. Our current priorities are to:

1) increase the effectiveness of the entire scientific enterprise;

2) dramatically improve science and mathematics education for all Americans; and

3) bring the wise use of science and technology to the center of national and international affairs.

These are ambitious goals, and accomplishing them will entail a long-term commitment from each of us. Let me describe each of these goals, in turn.

Increase the Effectiveness of the Entire Scientific Enterprise

If we are to be effective in increasing the vitality of the scientific enterprise, it is important that we analyze carefully how science works, and remind ourselves that it is the result of a highly creative process, very different from the mere measuring and recording of facts. To quote a strikingly thoughtful individual, the mathematician and philosopher of science, Henri Poincaré:

"In fact, what is mathematical creation? ... To create consists precisely in not making useless combinations, and in making those which are useful and which are only a small minority. Invention is discernment, choice. ... Among chosen combinations, the most fertile will often be those formed of elements drawn from domains which are far apart. — Most combinations so formed would be entirely sterile. But certain among them, very rare, are the most fruitful of all. ... The true work of the inventor consists in choosing among these combinations so as to eliminate the useless ones, or rather to avoid the trouble of making them, and the rules which must guide this choice are extremely fine and delicate."

Embedded here is the key to the dramatically increasing power of modern science: As more scientific knowledge is acquired about the world, it becomes easier to perform calculations or experiments that create new knowledge, causing knowledge to accumulate at an ever faster rate. Thus, there is an explosion in the number of Poincaré's useful combinations.

Each of us can look back on our own careers in science, see the accelerating pace of discovery, and trace its roots. Figure 1 is my schematic attempt to track my field for the period 1950–1985, emphasizing how knowledge was combined to create more knowledge, as biologists developed an understanding of how chromosomes replicate at the molecular level. My field is progressing even faster today, in large part because yesterday's discoveries have been used to create a diverse array of new research tools and insights. This difference is illustrated in Figure 2.

Even those of us in the midst of the dramatic biological discoveries of the past 30 years were incapable of foreseeing the powerful ways in which different bits of scientific knowledge could be combined. The reason for our lack of foresight was well stated by Einstein, who remarked:

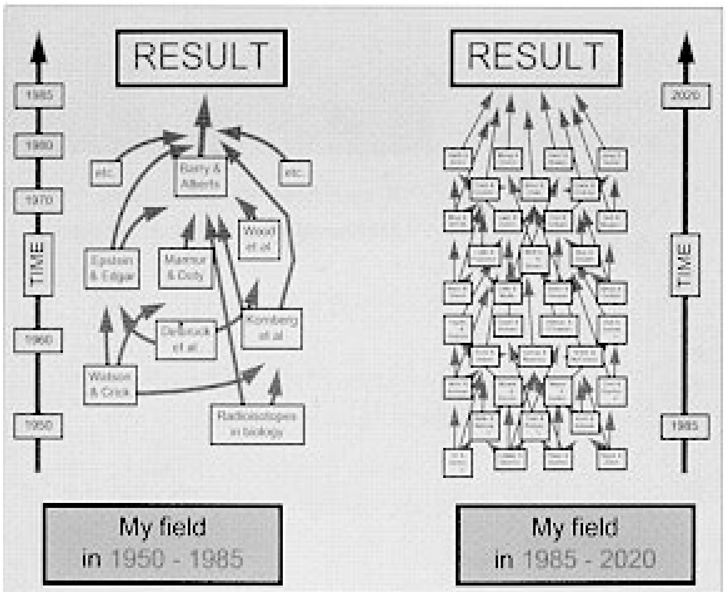

Figure 1

Figure 2

"The history of scientific and technical discovery teaches us that the human race is poor in independent thinking and creative imagination. Even when the external and scientific requirements for the birth of an idea have long been there, it generally needs an external stimulus to make it actually happen; man has, so to speak, to stumble right up against the thing, before the right idea comes."

But with increasing knowledge, a critical problem develops that retards the potential growth of science. Specialization reduces what each of us knows about other fields of science, and it greatly inhibits our ability to make new connections by "stumbling."

This is true even for neighboring fields that are certain to be useful to our own. For example, today my students and colleagues who are experts in cell biology know very little about the biology of human tissues, and vice versa. The situation is worse for more distant areas of science — consider chemistry and biology, for example [Figure 3].

One of our members, Jared Diamond, has emphasized this point in the current issue of *Discover* magazine. He gives an example of a paper published recently in a major scientific journal:

"The table of contents gives the title: 'Activation of SAPK/JNK by TNF Receptor 1 Through a Noncytotoxic TRAF2-Dependent Pathway.' In that entire title, the word *noncytotoxic* is my sole clue as to the subject of the article. ... Since I have been a professional biologist for 39 years and my research fields include cell biology, I am much more likely to be the article's intended reader than most other scientists. ... I went on to read the rest of the short report, but in the end I still didn't know what it was about."

Diamond goes on to say that the article may well reveal something that could lead him to make a breakthrough in his own research, but that he would never know from reading it. He also points out that most articles in other journals are equally inaccessible.

He ends by agreeing with Poincaré: "Unfortunately, great scientific advances come especially from applying discoveries in one field to another field entirely. ... Research described incomprehensibly loses much of its value."

The urgent need to encourage new connections provides a great opportunity for our own scientific journal, the *Proceedings of the National Academy of Sciences.* Although largely a journal of the life sciences in recent years, our Editor in Chief Nick Cozzarelli is making an intensive effort to widen its scope so that it better represents the scientific disciplines of the entire Academy. In doing so, it will be

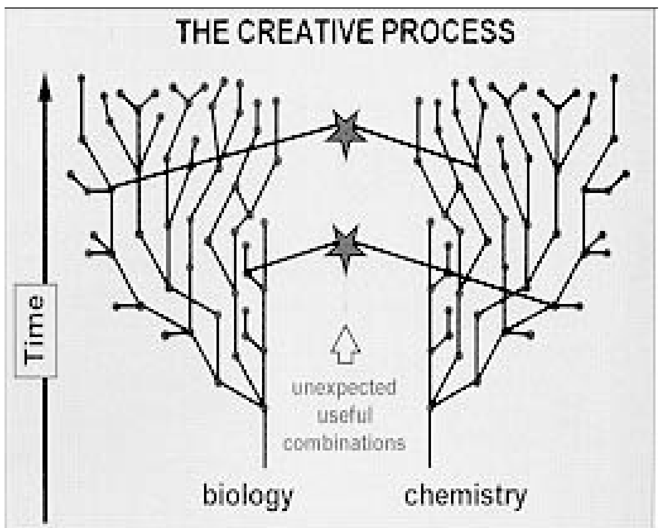

FIGURE 3

especially important to ensure that the journal's articles are written so as to be comprehensible to non-experts. If we are successful, our journal will serve as a special place where many new connections are made.

The Academy traditionally has put a great deal of effort into making new connections. In fact, we do this every time that we establish a new study committee at the National Research Council, working diligently to include every relevant expertise. A similar emphasis on cross-fertilization underlies each of our scientific colloquia, and it has been the driving force behind our enormously successful "Frontiers of Science" meetings. The Frontiers program is designed to bring together younger scientists — the future leaders of our scientific enterprise — and each year's meeting covers a very wide range of topics — from astrophysics to genetics, for example.

Of course, we also publish interdisciplinary reports that highlight special research opportunities. Consider our report on *Atomic, Molecular, and Optical Science*. Or the recent report of a workshop, published in the *Proceedings*, that linked researchers working on schizophrenia with a group of Academy members from diverse disciplines who initially knew almost nothing about this devastating disease.

Which leads me to ask: What about our universities? Are they doing enough to ensure intellectual cross-fertilization? Young scientists represent the future of scientific endeavors. The Academy has therefore been making a major effort to produce career and mentoring guides for students, and to make them freely available on our Web site. We also need to help the science departments in our universities recognize that their most important role is to educate a cohort of energetic young people who leave the university with a healthy new mix of skills and knowledge — for example, computer scientists or chemists who also have a deep understanding of biology.

Unfortunately, however, our university science departments tend to promote research that confines scientific interactions to within a single department. Wherever this occurs, it inhibits the type of stumbling that Einstein talks about, and it should therefore be energetically counteracted by university leadership.

Let me recount a recent success story at my own university, the University of California, San Francisco.

UCSF, like nearly all medical schools, was organized into the standard set of "basic science" departments which had been established some 50 years earlier: biochemistry, anatomy, physiology, pharmacology, and microbiology. It was universally agreed that the revolution in biology had long ago eliminated the intellectual justification for dividing the faculty and the students along these five lines. But to merge departments seemed to be more trouble than it was worth.

What took place instead was a complete reorganization of our central education mission, our graduate programs. In the past 10 years, we have established a new set of interdisciplinary graduate programs based on broad research areas: cell biology, structural biology, neuroscience, and so on. These programs themselves were not so unusual. What was unusual was the simultaneous abolition of all of the old graduate programs that were department-based.

Today our departments still exist. But their major role is administrative — most importantly, they no longer serve as a barrier to the "accidental" exchange of ideas. The whole vitality of the intellectual climate has thereby been enormously stimulated.

What about the government's role in the vitality of the scientific enterprise? The Academy needs to help our government maintain the appropriate strength and diversity in the nation's scientific portfolio. We have therefore been tracking the true federal investment in new knowledge — through the federal science and technology budget analysis that was recommended by our 1995 Committee on Allocating Federal Funds for Science and Technology, chaired by Frank Press. The results show that, in the period between 1994 and 1998, biological research funding will have risen by 9 percent, while research in the agencies that support the other sciences will fall by about 10 percent in real dollar terms [Figure 4]. Clearly, the American public is motivated to support biomedical research. We biologists must therefore do much more to emphasize the tremendous contributions to biology and biomedicine that come from advances in the physical and social sciences, as well as in math, computer science, and engineering. This is one important focus for our new "Beyond Discovery" series, whose aim is to increase the general understanding of science. This type of educational outreach is fully consistent with our important function as an adviser to government.

We are continuously emphasizing the importance of a robust federal investment in science, engineering, and medical research during this period of budgetary constraint. The Governing Board of the National Research Council recently produced a series of six papers, "Preparing for the 21st Century," that synthesize important findings from nearly 100 reports produced by the Academy complex. One of these papers focuses on science and engineering research in a changing world. In a joint statement issued with the papers, Wm. A. Wulf, president of the National Academy of Engineering, Kenneth Shine, president of the Institute of Medicine, and I reiterated our strongly held view that the present world leadership of the United States in science and technology cannot be maintained with a weakened federal investment in research. We also emphasized that more attention must be placed on rigorous merit review, so that precious federal dollars go toward funding only the best proposals and projects. Both these papers and the "Beyond Discovery" series have been distributed widely to members of Congress and to key policy-makers.

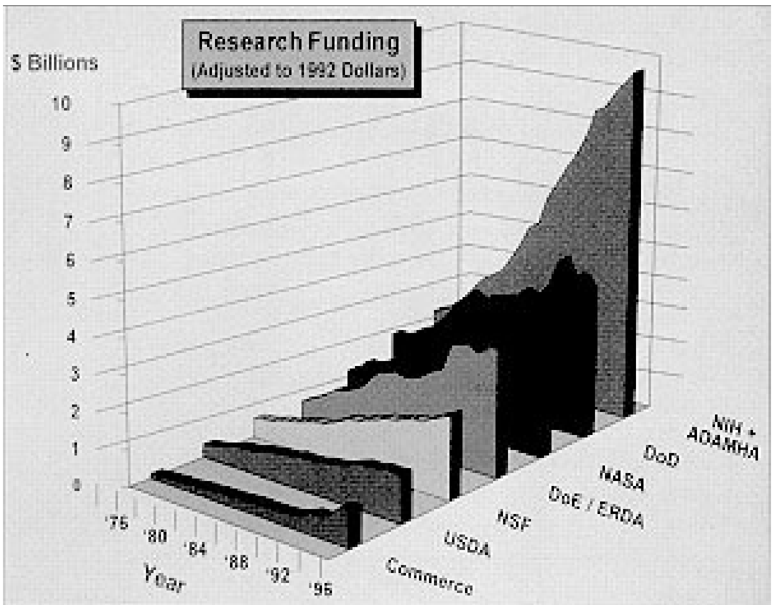

FIGURE 4

Dramatically Improve Science and Math Education for all Americans

I would now like to turn to the second major area of focus for the Academy: education. In December 1995, the National Research Council finished the daunting, four-year task of preparing the National Science Education Standards for kindergarten through 12th grade. The Standards stress learning science by doing science: that is, science as inquiry.

The aim is to make this kind of science a core activity for all students. This is important for creating wiser citizens and a more productive work force. It also is important for achieving the type of public understanding of science that will sustain public support of our enterprise.

Third International Mathematics and Science Study (TIMSS)

- Eighth grade results released November 1996 comparing 41 countries.
- U.S. performance was "average," being somewhat above average in science and somewhat below average in math.
- Essentially all students were randomly sampled in the 41 countries — therefore these are valid comparisons.
- List of countries compared:

Australia	Denmark	Japan	Scotland
Austria	England	Korea	Singapore
Belgium (Flemish)	France	Kuwait	Slovak Rep.
	Germany	Latvia	Slovenia
Belgium (French)	Greece	Lithuania	South Africa
	Hong Kong	Netherlands	Spain
Bulgaria	Hungary	New Zealand	Sweden
Canada	Iceland	Norway	Switzerland
Colombia	Iran	Portugal	Thailand
Cyprus	Ireland	Romania	United States
Czech Rep.	Israel	Russian Fed.	

FIGURE 5

What are the major barriers that prevent us from attaining the vision set forth in the National Standards? The data from the recent Third International Math and Science Study (TIMSS) is very helpful in this regard. As indicated in Figure 5, this major study involved 41 countries whose eighth-grade students were randomly sampled.

Among the many countries surveyed, U.S. performance in science and math was about average. This is not because a particular cohort of students in the United States performed especially poorly. Even if we look only at the best performers — those in the upper 10 percent of the nearly 300,000 students in the survey — the United States still looks average [Figure 6]. Countries such as Korea and Japan placed up to a third of their students in the world's top 10 percent; but only 5 percent of our students made it into this top group in math, and 13 percent in science.

Why did we do so poorly? For me, the most informative part of this survey was a series of videotapes, in which randomly selected teachers in the United States and Japan were observed teaching their eighth grade mathematics classes, and then were scored by experts. As you can see in Figure 7, none of the 100 U.S. teachers surveyed had taught a high-quality lesson. What is worse, 80 percent of the U.S. lessons, but only 13 percent of the Japanese lessons, received the lowest rating.

What is especially distressing to me is this: We have had National Standards in Mathematics since 1989, released by the National Council of Teachers of Mathematics and disseminated widely by our Mathematical

Sciences Education Board. Most of the U.S. teachers claim that they are familiar with these standards, and yet very few of the teachers who were videotaped showed evidence of this in their teaching. This means that we cannot hope to change the way teachers teach simply by having them read education standards. Real change requires a major effort in professional development, in which master teachers demonstrate new ways of teaching, allow the teachers to try the new methods, and then help them to continuously improve their practice. School systems must come to view themselves as professional development organizations. At a national level, we need to recognize and reward those school systems that serve as models in this regard. For example, in District 2 on the east side of Manhattan, 3 percent of the school budget each year is devoted to professional development, and the focus of the whole system is on increased student learning.

But there is a deeper lesson from the TIMSS results, one that is directly applicable to the professional lives of many Academy members. It is too easy to blame the teachers for the poor state of science and mathematics education. It is no wonder that so few of our precollege teachers teach science as inquiry. Almost none of them have ever experienced inquiry-based teaching themselves! We must accept a healthy portion of the responsibility for this state of affairs. Those of us who work at universities set the standards by which college science and mathematics are taught. We have given little thought to the fact that science teaching is almost entirely done by lecturing: After all, we were the "A" students who learned well in this way. But research findings tell us that most students require an active involvement in developing ideas, in order to gain any understanding of permanent value.

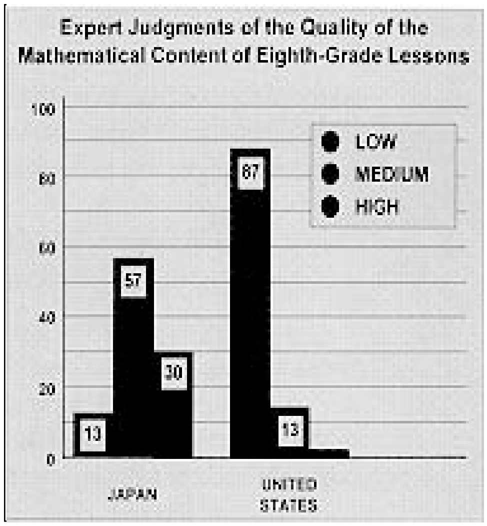

FIGURE 7

My field of biology provides a great example of how we fail to capture and hold student interest in science. As our knowledge of biology has exploded, the size of the textbooks used for introductory biology classes has grown accordingly. Biology 1 is generally believed to be a course in which all of biology must be covered in a single year and, under great pressure, biology classrooms therefore march through all of genetics, cell biology, ecology,

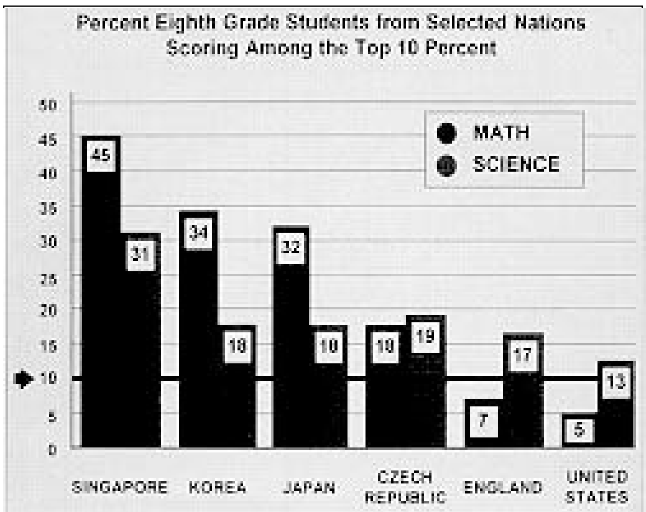

FIGURE 6

evolution, and so on — a task that becomes ever more daunting with each passing year of scientific discovery. There are more new vocabulary words to be learned than there are in a first-year course in a foreign language. The superficial coverage of all topics makes it impossible to teach any of them for any real understanding.

The college course has also created a monster with profound implications for the rest of our educational system, because it sets the model by which high school and middle school life science courses are taught. As a result, each of these courses also uses a textbook that covers all of biology.

To quote an astute observer of today's classrooms, professor of education Charles Anderson:

"Science as represented in most textbooks seems to be pretty dull and disconnected stuff, certainly not something that most children would want to find out about in their spare time. Even more troubling, the culture of most classrooms where those textbooks are used has little in common with the culture of adult science. Most adult scientists, for example, spend relatively little time copying facts and definitions out of books, yet that is the primary activity of many students in science classes. For many children, exposure to science textbooks and to the culture of science classrooms results not in understanding, but in alienation from science."

This brings me to what I believe to be the major limiting factor in science education reform. Until we teach science as an inquiry-based process in our introductory courses in college, we will have to rely on a massive retraining of teachers by school districts if we are ever to expect our nation's science teachers to teach according to the National Science Education Standards.

Through our Committee on Undergraduate Science Education chaired by Bradley Moore, the Academy has been attempting to convey this message to colleges and universities. Two of our recent publications are especially relevant. One is *From Analysis to Action*, a report of a major convocation chaired by Donald Kennedy which calls for major changes in our college courses. The other is *Science Teaching Reconsidered*, a handbook that is designed to help professors try teaching methods other than the standard lecture. On its cover is a photograph that reminds us of Eric Mazur's physics course given to hundreds of students in a large lecture hall at Harvard. He interrupts his lecture every 15 minutes with a conceptual question, which the students discuss for a few minutes in small groups. Mazur reports great success in keeping the students involved and increasing their understanding.

Bring the Wise Use of Science and Technology to the Center of National and International Affairs

The last of my three priorities has long been central to the Academy. Those who understand the role of science and technology in a productive economy have a very clear vision of its importance for all nations. To build stable societies, one needs to make wise use of natural resources and to use water and produce food and energy in sustainable ways. To do so will require constant intervention by individuals trained in science and technology. It is not sufficient to make use of outside experts who fly in and out of a country as paid advisers. The expertise must be strongly integrated into the fabric of each society. Without such wisdom at the local level, development brings a destructive emphasis on short-term consumption, with little concern for the long-term provision of natural resources.

We soon will have available to us remarkable new technologies that will make possible economical, nearly instantaneous communication throughout the world — requiring only a low-cost computer and a modem. This rapidly developing communications network could create a qualitatively different type of world science, in which local experts in Africa, for example, can gain rapid access to appropriate science, technology, and medical advice, regardless of where that information is located. This point has been emphasized in our just-released National Research Council report, *Bits of Power.* The study committee, chaired by Steve Berry, stressed that efforts to expand computer network access in poor countries will benefit all nations, because scientists throughout the world have valuable information to share.

The National Research Council and the Academies have been placing great emphasis on increasing our interactions with important international agencies, including the State Department and the World Bank. We are making steady, but slow, progress. To get their attention, we need to do a much better job of explaining to international policy-makers how scientists and engineers can make major contributions to all areas of international development. And, we should repeatedly emphasize Jacob Bronowski's crucial observation that "Science has humanized our values." As we spread science and its values throughout the developing world, we not only provide a strong force for sustainable development; we also support democracy.

Scientists worldwide share a common culture, which enables us to feel easily at home with all scientists, regardless of their country of origin. Last January, the five officers of this Academy participated in an intensive two-day meeting in Beijing with the leaders of China's scientific enterprise. Our discussions were remarkably open and frank, and we found that we shared a wide range of interests. At this time in world history, when the cultural and historical differences between, and within, nations seem to be increasingly causing conflicts, it is reassuring to know at least one culture — science — is shared worldwide. Remembering the close personal relationships between U.S. and Soviet scientists that helped to diffuse tensions throughout the Cold War, we can dream about creating a strong network of international connections among all scientists that can serve as a conduit to world peace.

Viewed in this way, an important focus for the Academy's international activities becomes the creation of close personal ties among today's leaders of our respective scientific enterprises, as well as among the younger scientists who will be tomorrow's leaders. Indeed, we are already hard at work on this goal. Some of the current activities of the Office of International Affairs are shown in Figure 8. Here I have selected activities that have brought scientists together to work on meaningful challenges, thereby creating lasting bonds among scientists worldwide.

For scientists to be more influential at home and abroad, it also is important that we work to enhance our connections to the rest of society. I have tried to make this clear by means of a simple diagram [Figure 9]. We tend to define the scientific community today as containing only those individuals who do scientific research. As I have emphasized on other occasions, this is a narrow and counterproductive view of science. It is both in the interest of our nation and in the interest of scientists to expand our view of our community, so that it includes science teachers, science journalists, and others who use science — in government and in many other professions. In addition, we must

Making New Connections Between Scientists Across the World

- Three new "Frontiers of Science" annual meetings, connecting 40 future leaders of U.S. science with their counterparts in Germany, Japan, and China, respectively.
- Young investigator program, in which teams of 6 to 10 scientists conduct joint summer studies focusing on particular sustainability issues.
- Middle East collaborations — joint study nearly completed on sustainable water resources, using commitee that includes three members each from Israel, Jordan, and the West Bank and Gaza.
- Collaborations with Mexico using joint committees to study the Mexico City aquifer, oceanographic research, and environmental issues along the Mexico-U.S. border — as well as to review the graduate programs at the Universidad Nacional Autónoma de México (UNAM).

FIGURE 8

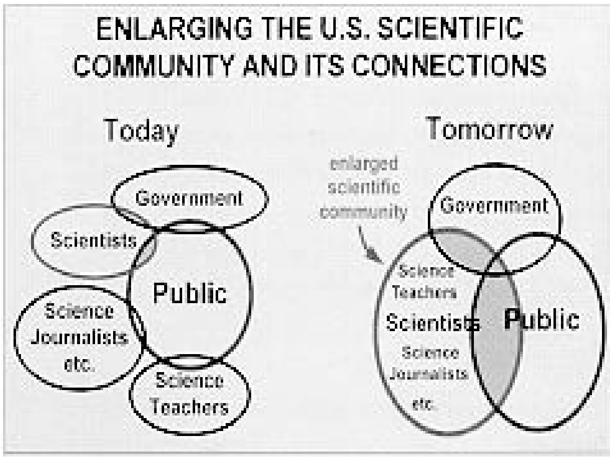

FIGURE 9

work to increase the amount of overlap between this enlarged scientific community and other elements of our society. Through such connections, we can give our fellow citizens a much better understanding of science and its values. We can also spread our values more widely.

Measuring What Counts

Throughout this talk, I have repeatedly emphasized that scientists need to pay more attention to community building of all kinds: among scientists of diverse disciplines, among scientists with similar interests throughout the world, and between scientists who do research and those who use science in other ways. I would like to end my talk by emphasizing a major responsibility of scientists, which is so important that I will state it as a theorem and corollary.

Theorem: What is measured in high-stakes assessments has a profound effect on human behavior.
Corollary: We must be exceedingly careful to make sure that we measure what counts!

If we are to increase the effectiveness of the scientific enterprise, we must pay close attention to helping our young scientists make the type of unexpectedly useful connections that Poincaré described. To this end, our evaluation systems must do more to encourage innovation and risk-taking. Given an increasingly competitive environment, and an unfortunate sense that the quantity of one's publications is being measured, most young scientists will do the safe thing by continuing along the research paths of their professors. As a result, in some fields of biology today we often find that the same observations are published simultaneously by three or four different laboratories. Meanwhile, there are vast unexplored areas of research that no one seems to be probing.

Therefore I suggest that all evaluations of excellence in science explicitly include a focus on innovation and uniqueness. For example, researchers seeking funding should be asked to do more than just describe their planned experiments in grant applications. They should also be asked to explain in what ways their work is unique, and to point out those aspects that they believe to be most innovative.

We also need to measure what counts when we assess student learning. We cannot have science taught as inquiry so long as our college entrance exams test for word associations and memorization. Today's vocabulary-laden high school textbooks teach to the tests; likewise, the tests reflect the textbooks. This self-reinforcing feedback loop must be broken — starting with new tests.

Internationally, we cannot hope to attain sustainable world economies until we find a better measure for economic success than the Gross National Product (GNP). After all, a developing nation can easily increase its GNP by harvesting all of its forests for lumber. It is widely recognized that we need much more sophisticated measures of national productivity. In fact, the National Research Council presently has several study committees that are hard at work on these issues. One of these is our Board on Sustainable Development, led by Ed Frieman and Robert Kates.

Why have I chosen to end my talk with this discussion of measuring what counts? Precisely because for U.S. science, and indeed for much of international science, it is the 2,100 members of this Academy who largely determine what is most valued in the scientific enterprise. It is we whose judgments influence the career paths of many younger scientists — and it is we who often determine who is, and who is not, considered a scientist. If we convey the message that those who do not do scientific research are not part of our community, then science teachers and others will remain isolated and unsupported. If we fail to value the type of science that is needed to promote wise international development and the efficient use of resources, then this type of science can not flourish to solve world problems. And if we fail to appreciate the types of science done outside of our own disciplines, or place little value on the bold attempts of younger scientists to stray from conventional research topics, we shall hinder rather than help forge the path toward novel discoveries.

The views of the members of our Academy are more important to the future of the world than you may think. We must carefully consider what we value, and then do what we can to make sure that these are the values by which our society measures itself. Only then can we hope to move the nation and the world in directions that we can proudly defend to our grandchildren.