PART 1

The 2000 William D. Carey Lecture

Rita R. Colwell took office as director of the National Science Foundation (NSF) in 1998. Prior to becoming NSF director, she spent seven years as president of the University of Maryland Biotechnology Institute. During her tenure at the University of Maryland, she also held the positions of professor of microbiology, director of the Sea Grant College, and vice president for Academic Affairs for the University of Maryland System.

Colwell began her career as a researcher and educator in 1956 at Purdue University in Indiana. In 1958, she joined the University of Washington, where she held the positions of predoctoral associate and assistant research professor. She has been guest scientist at the National Research Council of Canada, and was a member of the biology faculty at Georgetown University.

She has authored or co-authored 16 books and more than 500 scientific publications, and has received numerous awards, including the Medal of Distinction from Columbia University, and the Andrew White Medal from Loyola College. She has also been awarded nine honorary degrees from institutions of higher education and has held several honorary professorships.

Colwell has been the chairman of the Board of Governors of the American Academy of Microbiology, and president of AAAS, the Washington Academy of Sciences, the American Society for Microbiology, the Sigma Xi National Science Honorary Society, and the International Union of Microbiological Societies. She was also a member of the National Science Board from 1984 to 1990.

In her lecture, “The Wellspring of Discovery,” Colwell celebrates the 50th anniversary of the National Science Foundation and its role as the source of inspiration “to probe frontiers we can only begin to imagine.” She compares the role of the NSF to oceanic thermal vents—”black smokers”—which sustain the surrounding species in much the same way that the NSF sustains scientific research: “I have come to view NSF not so much as a government agency, but rather as a source of ideas and discovery, as a wellspring ... of creativity.”

Colwell takes great pride in the successes of NSF supported projects, including ARPANET, NSFNET, and the Mosaic Web browser, which together have evolved into the ubiquitous Internet. She observes that

NSF funded research has led to the discovery of Polymerase Chain Reaction, improved eye surgery procedures, and a better understanding of cause and effect of El Niño. Most striking is her reminder the that "in the last 25 years, [NSF has] funded 78 researchers who subsequently went on to win the Nobel Prizes in their respective field."

Not content to rest on her agency's laurels, Colwell outlines her vision of the future of science. She advocates the "K-through-Gray" approach to education, stressing lifelong learning and a trainable (retrainable) workforce, the urgent need for society to alter the reputation of mathematics, and to explore the intersections between art and science. Art and poetry draw us back to the wellspring. She concludes: "Bill Carey helped to tap this wellspring. For the sake of scientific discovery, and to continue to nourish our economy, it is now up to all of us to sustain it."

"The Wellspring of Discovery" was presented as the twelfth annual William D. Carey Lecture in Washington, DC, on April 11, 2000. The Carey Lecture was established by AAAS in honor of Bill Carey on the occasion of his retirement as executive officer of AAAS, a post he held from 1975 until 1987. During his tenure, Carey catalyzed the study of the role of research and development in the federal budget and introduced initiatives that now form much of the landscape of the current AAAS programs, including publication of this Yearbook.

The Carey Lectureship recognizes individuals who exemplify Bill Carey's leadership in articulating public policy issues that are engendered by the application of science and technology. Lecturers are selected by a distinguished advisory committee.

1 The Wellspring of Discovery

Rita R. Colwell

This year marks the 50th anniversary of the birth of the National Science Foundation (NSF). Our golden anniversary gives us the opportunity to reflect on NSF's role as the wellspring for discoveries. It also provides inspiration for us to probe frontiers we can only begin to envision. As we look at some milestones since NSF's creation, I will add a few of my own musings from a career in science over much of this same time period.

As a scientist, particularly as a biologist contemplating NSF's beginnings and its subsequent contributions, I think of a discovery in the depths of the ocean that can serve as a metaphor to set the stage. I am referring to the mineralized chimneys called "black smokers" that form around the hydrothermal vents at the bottom of the sea and tower above the communities of life thriving around them at these unlikely depths. The mouths of these vents spew forth boiling water full of chemicals, creating conditions that are toxic to humans and to most other life forms. We first discovered these communities two decades ago, and since then we have discovered over 300 species inhabiting these vents, all of them living in the depths without photosynthesis. Instead of using the sun's energy they employ chemosynthesis to oxidize the hydrogen sulfide emerging from the vents.

To me, the black smokers are not only metaphorical but also literal wellsprings of discovery. Some have even suggested that these springs could have been the birthplace of all life on our planet. Here we see how basic research has taken us to one of the most extreme environments on Earth and brought back discoveries whose implications we have just begun to fathom.

Rita R. Colwell is director of the National Science Foundation. This article is based on the William D. Carey Award Lecture delivered at the 25th Anniversary AAAS Colloquium on Science and Technology Policy, held April 11–13, 2000, in Washington, DC.

Returning to the Earth's surface, I would like to explore another origin: the beginning of NSF. William D. Carey, for whom this lecture is named, helped to bring the Foundation into being. He was a deep thinker on matters both intellectual and emotional, gruff but with a big heart. While he was at the Bureau of the Budget, he was the main advocate in the Administration for creating a national science foundation. It was his perseverance, openness, and political savvy that helped carry the day. Ultimately, with Bill Golden, John Steelman, and others, he helped to break a logjam holding up legislation to establish NSF.

Interviewed later, Bill Carey recalled *Science—The Endless Frontier,* the report by Vannevar Bush that sketched out the need for a science foundation. "There was a sense," he said, "that the report had a valid and urgent message and that if somebody didn't pick this up and move with it, it could be quite a national loss. . . ." Elsewhere he recalled the excitement of those years. "You have to think of the atmosphere," he said. "This was postwar, most of the world in ashes, the U.S. riding very, very high, dreaming great dreams. . . . There was to be a new age of science and creativity. . . . We were building a brave new world and all would go well. There was a very short window of idealism and optimism that closed very abruptly."

Bill also said, "I don't think any of us ever imagined we were inventing a $3 billion research investment enterprise." (Little did Bill Carey imagine our current hope that $4 billion for this year's budget is just the beginning!) Bill Golden also helped by advising President Truman that NSF should devote itself to fundamental research. As it happened, it took five years of debate over how the support of the "best science" could be reconciled with the pluralism of America. I think we all agree that this discussion has never stopped and that it has been, and continues to be, a healthy exchange.

In any case, on January 4, 1950, President Harry S Truman delivered his State of the Union message. The speech is full of the tenor of the times, conscious of the war just passed. It recognizes the Nation's entry onto the global stage and conveys a sense of great opportunity, but also a sense of fateful choice. I would like to share a passage from that speech, in which the President calls for the establishment of NSF:

> The human race has reached a turning point. Man has opened the secrets of nature and mastered new powers. If he uses them wisely, he can reach new heights of civilization. If he uses them foolishly, they may destroy him. . . . To take full advantage of the increas-

> ing possibilities of nature we must equip ourselves with increasing knowledge. Government has the responsibility to see that our country maintains its position in the advance of science. As a step toward this end, the Congress should complete action on the measure to create a National Science Foundation.

That following May (on May 10, 1950) President Truman's train stopped in Pocatello, Idaho, and that was where he signed S. 247, the act that created NSF. In 1951, President Truman nominated Alan T. Waterman as NSF's first director. Vannevar Bush described Waterman, chief scientist at the Office of Naval Research, this way: "He is a quiet individual, a real scholar, and decidedly effective in his quiet way, for everyone likes him and trusts him." Waterman ended up serving two six-year terms, with the early years of his tenure marked by argument over NSF's mission. The crux of it was this: The Bureau of the Budget wanted NSF to evaluate science programs across the federal government. Waterman and the science board, however, considered the top priorities to be support for basic research and graduate education. Thankfully, Waterman eventually prevailed.

NSF received its first real budget in 1952. The appropriation was late, and totaled only $3.5 million, a far cry from what Vannevar Bush had proposed. The first NSF grant (for $10,300 over three years) went to Sidney Weinhouse at Philadelphia's Institute for Cancer Research. That year, NSF gave out a total of 97 research grants to biological, medical, mathematical, and engineering sciences.

Besides the transition from a budget of $3.5 million to one of almost $4 billion, we have seen major changes over these 50 years in how the federal government supports science and technology. We have moved from a massive infusion of funds into physics and engineering to a recognition that all disciplines must be nourished. We have watched science and engineering become a truly global enterprise. Disciplinary boundaries established for convenience now recede in significance, with some perhaps disappearing altogether. Information technology accelerates the intersection of the disciplines and drives our progress.

I speak from personal experience when reflecting upon how our enterprise of science and technology has evolved over these decades. I also speak as a believer in the power of basic research to improve lives, sometimes unexpectedly and sometimes as a result of directed leadership. In addition, I have always been intrigued by the complexity of the world we live in. Reductionist science, dissecting the whole into the smallest parts, seemed to me like clearcutting a forest in order to study one tiny seedling. I have always been more interested as a biologist in how it all comes together—intrigued by the mixture, by the froth that makes life bubble. I have spent more than 30 years studying cholera, a terrible water-borne scourge that still kills thousands every year in developing countries. Today we have reached the point in our research where women in Bangladesh are testing a simple filtering system for their drinking water, using sari cloth to remove plankton and particulate matter to which the cholera bacteria are attached. To get to this point took decades of study for us to define the life cycle of the organism that causes cholera.

New technologies, notably information technologies and satellite remote-sensing, have been an integral part of this work. For example, during the 1960s, I was the first American scientist to develop a computer program to analyze taxonomic data for marine bacteria. This research eventually led to a conclusion that was considered radical at the time: The strain of cholera found in outbreaks of the disease belongs to the same species as harmless strains found everywhere in brackish waters, estuaries, and coastal waters. Very recent data indicate that the bacterium is even part of the mesophilic community that lives not far from the hydrothermal vents in the ocean. Here we see once again how things come together.

I have seen firsthand the power of meeting other disciplines more than halfway. We gain a richness of vantage points at different scales, such as the broad view provided by remote-sensing techniques. In recent years, satellite data have shown how global environmental change influences the spread of cholera. Further refinements to those techniques could help us save thousands of lives a year by effectively monitoring and predicting conditions conducive to cholera epidemics. Without remote-sensing, developing models to allow proactive measures against the disease would be difficult, if not impossible.

During these years as a researcher, I have come to view NSF not so much as a government agency but rather as a source of ideas and discovery, as a wellspring, if you will, of creativity. Our role at NSF is not so much to sustain as to spark discovery. Indeed, the 50-year mark is an appropriate juncture at which to consider what impact NSF has had as a generator of discoveries. Let me begin by putting the agency in perspective: Of the national research and development expenditures, the federal government accounts for barely one-fourth of the pie.

Furthermore, NSF is a small player here, accounting for only 3.5 percent of the total federal investment in research and development. It is a very important 3.5 percent, however, because it underwrites nearly one-quarter of all federal support for basic research at academic institutions.

We can look at one increasingly familiar measure of success: patent citations. Half the citations on patents refer to articles originating in academe; in mathematics, the life and biomedical sciences, and clinical medicine, the percentages are even greater. In archival journals, nearly two-thirds of the papers cited on patents were published by organizations primarily supported by public funding. It is one measure of how publicly funded research produces the knowledge that spurs innovation. We are also seeing the connections multiply between university and industrial science. While industry spends an increasing amount on research, its dependence upon publicly funded research has grown even faster.

The number of these citations has increased explosively, from 13,000 in 1990 to over 100,000 in 1998. We have seen a ten-fold increase since 1988, and a doubling in the past two years. Granted, some of this increase comes from our new abilities to search online by computer, but that does not explain the entire trend. We can zoom in to look in finer detail at where academic patents are being granted, and we find that the three largest classes of academic patents all have biomedical applicability.[1] At the same time, the National Institutes of Health (NIH) receive over half of the federal funding for academic research. That will continue to work only if we maintain a healthy foundation of basic science and engineering research from which the life sciences can draw.

In federal research funding over the past three decades, a major increase has gone to the life sciences, while the shares going to engineering and the physical sciences show the opposite trend (major drops in their share of funding). While NIH is concentrating on the biomedical sciences and psychology, NSF is building up computer science, basic engineering, and the physical sciences, and in the non-medical areas of the life sciences, NSF provides the majority of federal funding. Our support is truly the wellspring into which other fields can tap. With this in mind, and with the worrisome slowdown in funding for mathematics and physical science, and with the shares out of balance, we must ask whether it is possible to deplete pools of knowledge. Will the source run dry?

As we take stock, it is instructive to look at some of the discoveries we can trace back to NSF. As the agency has grown, the rivulets flowing from the source of fundamental research have turned into rivers following unexpected courses. We can follow the channels formed by ideas as they gathered enough momentum to carve pathways for new ways of thinking. I would like to recount just a few of these stories, emphasizing that these are only examples drawn from a wealth of discoveries.

The first example is the Internet. It is ironic that so few people realize that key advances in Internet technology were spurred by federally funded research. What we know today as the Internet grew from predecessors in the 1980s and earlier, notably ARPANET and NSFNet. The high-speed backbone called NSFNet was a research and education network used to link our supercomputer centers to universities. It helped to demonstrate the effectiveness of networking technology. During this same early period, scientists and students from NSF's supercomputer center at the University of Illinois developed the first Web browser (Mosaic), which moved the Internet from the realm of esoteric university research to public communication and commerce. Now, of course, millions use the Internet daily.

We turn to the hot springs of Yellowstone National Park for another example of an unexpected outcome: the development of the Polymerase Chain Reaction (PCR). This technique, developed in the private sector, is used in molecular biology to clone a small fragment of DNA and produce multiple copies. The technique we call DNA fingerprinting has wide application in genetic mapping, medicine, forensic science, and even tracking environmental pollution. The polymerase used today was extracted from a heat-resistant bacterium, which itself was isolated from a Yellowstone hot spring through NSF-funded research. (In fact, Thomas Brock of Indiana University found the bacterium while working out of a trailer in the park.)

Another serendipitous story involves the standard procedure for cornea repair, the "flap and zap." In this procedure a mechanical blade cuts a flap of cornea, an eximer laser removes tissue, and then the flap is replaced. The problem was the coarseness of the initial cut, and a solution was discovered entirely by accident. In 1993, a student was conducting research at the University of Michigan on a femtosecond laser. This laser emits light roughly a billion times faster than an electronic camera flash. While the student was working, the ultrafast laser accidentally entered his eye and he was rushed to the hospital. The examining doctor was amazed to find a perfectly round laser burn, which was far more precise than the slower-pulse lasers the surgeons had been using. The examining physician said, "You're fine. But tell us about this laser!" The use of the femtosecond laser is now in the clinical trial stage.

Sorting out the irregular oscillation of the atmospheric and ocean conditions that we call El Niño is another success story. In the early 20th century, British mathematician Gilbert Walker first noticed the link between the monsoon rains failing to occur in India and the atmospheric pressure in the eastern South Pacific and the Indian Ocean. But unraveling this puzzle required advances in technology, both in computing techniques and in gathering massive observational data sets. Also, atmospheric and ocean scientists had to work together to reveal El Niño's secrets. Today, we can warn the populations at risk in Indonesia, Ecuador, or California months in advance that droughts, rains, and other severe conditions are on the way.

Tracing the complexity of our world is still another challenge. It is one of our more diffuse achievements, with payoffs that we are just beginning to explore. The prize, though, is nothing short of mapping the underlying order of the universe. The perspective of complexity, with its mathematical underpinnings, helps us to see into both the physical and the living realms, and to probe their interconnections. Complexity brings insight into many worlds, from artificial intelligence to economics, from ecology to materials science, and beyond. It gives us a perspective spanning all fields and all scales, and a richness across different orders of magnitude. We now know that many systems, such as ecosystems, do not respond linearly to environmental change. Up to now, we have sought understanding by taking things apart into their components. Now, at last, we have begun to map out the interplay between the parts of complex systems.

Even more important than the ideas and the technologies flowing from NSF's efforts are the lives enriched by our activities. In NSF's very first program budget, over a third went to predoctoral and postdoctoral fellowships. E.O. Wilson, the two-time-Pulitzer-Prize-winning biologist who is at Harvard today, was a member of what we call the "NSF Class of '52." He recently recalled, "The announcements of the first NSF postdoctoral fellowships fell like a shower of gold on several of my fellow students in Harvard's Department of Biology on a Friday morning. . . . I was a bit let down because I wasn't among them, but then lifted up again when I received the same good news the following Monday (my letter was late)." I guess some things never change.

There are other measures of investment. In the last 25 years, we have funded 78 researchers who subsequently went on to win Nobel Prizes in their respective fields, with 27 in physics, 22 in chemistry, 13 in physiology and medicine, and 16 in economics. Today, we estimate broadly that nearly 200,000 people each year participate directly in NSF programs and activities. These participants include researchers, postdoctoral students, undergraduates, and K-12 students and teachers. In another growing realm—that of informal science education—our support flows to much greater numbers of people. Projects we support at museums, science centers, and planetaria touch about 50 million people each year. The figure doubles to 100 million for the audiences of radio, television, and film programs on science. One example is the children's television series called "The Magic School Bus." In its heyday it was carried by 300 public television stations in the United States. Over three million children watched the show weekly, making it the top-ranked series among young people. It was such a success that it is now being picked up by commercial stations.

Other institutional approaches by NSF have also had a measurable impact on people. Our Engineering Research Centers (ERCs) are now 15 years old and span all areas of science and engineering. From the very start they promoted a new culture of integrated research and education: Students have industrial mentors, while industry representatives work within the centers. In fact, the ERCs are now recognized as the "flagship" of a new kind of engineering education. The numbers of patents, inventions, and spinoff firms are impressive, but another finding speaks to a much more important result of basic research. In surveys of companies that partner with the centers, 40 percent of the firms said that one of the most significant benefits they received was hiring students who gained experience at the center. Employers say that center students understand industry better, get up to speed more quickly, communicate better, and are more adept at cross-disciplinary approaches.

A quite different but equally successful approach is the Louis Stokes Alliances for Minority Participation, which target the underrepresentation of minorities in science and engineering. Begun in 1990, the program links two- and four-year educational institutions, as well as business, industry, and government. There are now 28 Alliances across the United States. A key feature of their success is a summer "bridge program" to help high school graduates prepare for college, as well as to give them research experience and mentoring. This program has had a strong impact on the number of degrees awarded to minorities in Alliance institutions. In 1990, before the program began, the degrees in the first group of institutions totaled 3,914; by 1999, this had increased to 7,253. For all the Alliance institutions, the total by 1999 was 20,567 degrees. Overall, a very conservative estimate is that our Alliance institutions awarded over half of the total bachelors' degrees given in science and engineering to minorities in 1997, and this number is growing. That is success by any measure.

Now comes the hard part: These successes give us an all-too-tempting invitation to rest on our laurels. On the one hand, our surveys document strong interest by the public in science. At the same time, we see skepticism, and sometimes outright anxiety, about a host of areas—from genetically modified foods specifically to technology in general. We see the popularity of programs such as "The X-Files" and the daily astrology columns in major newspapers. Just as disturbing is the fact that many of those kids who climbed aboard the Magic School Bus before kindergarten have climbed off by the time they reach middle school.

All of these issues sketch the larger dimensions of the challenge we face. The coming years will be anything but business as usual. The global economy is changing too rapidly for any of us to stand still. In this new economy, information has moved to center stage and knowledge has become the currency of everyday life. To date, we have managed to cope with these changes quite comfortably by relying on imported talent. As a firm believer in the internationalization of research, I have and will continue to voice my support for cooperative activities and exchanges of all kinds. I nevertheless believe that we should also consider the words of Demetrious Papademetriou of the Carnegie Endowment for International Peace. In a recent op-ed in the *Washington Post,* he reminded us that our reliance on imported talent is at best a short-term strategy. In his words, ". . . the rest of the developed world is waking up to the fact that America's cherry-picking of international tech talent amounts to an enormous competitive advantage." He further points out that other nations now compete with us for top talent. We are also seeing the suppliers of this talent base making greater efforts to keep it close to home. All of this could spur us to changes that are long overdue.

For starters, we can begin to weave together the different levels of our educational systems, through what has been called the "K-through-Gray" approach. It supplants the antiquated notions that knowledge is gained in so many semesters and that only after completing certain prerequisites can we be pronounced to be "educated." What is called for is a system of never-ending, lifelong learning that promotes versatility and flexibility. This idea is tied in turn to the notion that we need more than a highly trained work force. We need a highly trainable work force—

and a retrainable work force. A university or college graduate in 2000 can expect to change careers four to seven times before retirement. We know that information technologies have created this dynamic, but they also supply the tools and means to embrace it, as they bring resources for learning to anyone, anywhere. Our universities and other educational institutions face the challenge of reinventing themselves for a seamless system of learning over a lifetime, cradle to grave. Here I must add that this is one area where NSF is practicing what it preaches. Some of our newest investment priorities, such as the Graduate Teaching Fellows Program and the Centers for Learning and Teaching, exemplify the kind of positive change we are hoping to foster at all educational levels.

All of these changes—the transformation of science, the pace of technological change, the glimmerings of public dissatisfaction with new technology, the remaking of the world economy—raise challenges enough for the next 50 years and beyond. Yet I would like to go one step further. Engineering and the sciences enrich our lives. They are part of what defines us. Science connects with the humanities and the arts in a way that, for the first time in generations, creates hope for us to transcend, at last, the "two cultures" of C.P. Snow. In this vein, I was recently surprised by the limited vision expressed in an article in the *Washington Post Magazine* that was authored by the essayist Henry Allen. He talked about the "gray lives" given to us by "our dead world of science." Such a lament, from such an erudite cultural critic, suggests to me a poor exposure to science. I would counter it with Richard Dawkins' words from his book, *Unweaving the Rainbow:*[2] "The feeling of awed wonder that science can give us is one of the highest experiences of which the human psyche is capable. It is a deep aesthetic passion to rank with the finest that music and poetry can deliver."

Our new capabilities give us new ways to explore the intersections between art and science. Some of the wealth of the world's art is already available to anyone with a computer. Mark Levoy and others at Stanford University in California use three-dimensional scanning techniques based on fundamental mathematics to create a digital collection of Michelangelo's statues. The team records a thin sheet of laser light as it sweeps over a sculpture, transcribing the data as a grid of points in three-dimensional space and producing a mesh of triangular images. The detail is fine enough, says Levoy, "to capture the chisel marks of Michelangelo." Such records could transform methods of archiving and studying sculpture and architecture. In fact, University of Washington computer scientists are actually reproducing replicas of statues. Even viewers of the actual statue can look at it in a new way by using a nearby computer to zoom in on parts difficult to see from the ground, transforming art-viewing from a passive to an active experience, as Levoy points out.

Another embodiment of the intersection of art and science is the modern sculptor Helaman Ferguson, who is also a mathematician. He creates mathematical formulas in stone with a chisel guided by a computer, expressing the duality of both art and mathematics as universal languages. Still another artist who merges art and science is Marty Quinn, who has written a "Climate Symphony" based on the oscillations of climate change. A new work by Quinn will capture the experience of an earthquake as music, simulating the reception of earthquake waves at different times around the world.

We are now recognizing an urgent responsibility to transform how our society thinks of mathematics. We want to change its reputation as an object of incomprehension and fear. We want, instead, to inspire appreciation of its poetry and recognition of its utility in helping us to sort out the complexity of our world. As K.C. Cole writes in her book, *The Universe and the Teacup,*[3] "Mathematics seems to have the astonishing power to tell us how things work, why things are the way they are, and what the universe would tell us if we could only learn to listen."

Or if we could only learn to see. The photography of Felice Frankel, artist-in-residence at the Massachusetts Institute of Technology, has captured beautiful scientific images of such unlikely subjects as vials of nanocrystals, patterns of bacterial colonies, a hologram of plastic, and a peeled polymer. "Too often the visual beauty of science research seems to be kept secret," Frankel believes. "Scientists are trained to be suspicious of visually stunning displays . . . and thus remain largely unaware of the value of the visual poetry of their own work. . . ."

Many of us in science are drawn to the words that end the poem of T.S. Eliot called the "Four Quartets:"

> We shall not cease from exploration
> and at the end of all our exploring
> Will be to arrive where we started
> and know the place for the first time.
> Through the unknown remembered gate
> When the last of the Earth
> was left to discover
> Is that which was the beginning.

These are magical words, for they draw us back to the wellspring and nourish our inspiration. Bill Carey helped to tap this wellspring. For the sake of scientific discovery, and to continue to nourish our economy, it is now up to all of us to sustain it.

Endnotes

1. The three largest academic utility patent classes are chemistry/molecular and microbiology, class 435; drug/bio-affecting and body treating composites, class 514; and drug/bio-affecting and body treating composites, class 424.
2. Dawkins, Richard. *Unweaving the Rainbow.* Houghton Mifflin Company; Boston, MA. 1998.
3. Cole, K.C. *The Universe and the Teacup: The Mathematics of Truth and Beauty.* Harcourt Brace. 1998.