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National Research Council
"Innumerable Connections"

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[no slide]

I'm very pleased to have been invited to address you during such a momentous week--the week of our presidential vote, and an outcome that even our best mathematical skills could not help us to foretell. I'm reminded of the way Winston Churchill described the skill of a politician. It was, he said,

> "the ability to foretell what is going to happen tomorrow, next week, next month, and next year. And to have the ability afterwards to explain why it didn't happen."

Whether it did or didn't happen I will leave to you to decide. However, as I thought about what I wanted to say to a gathering of mathematicians, I remembered something that happened to Stephen Hawking. As he was writing his famous book, A Brief History of Time, he was told that every equation he included in the book would cut sales in half. "I therefore resolved," Hawking said, "not to have any equations at all." I have absorbed Hawking's lesson and I do not intend to include any equations today. I would, however, like to mention one significant number: 13.6 percent. We are delighted that Congress has raised our budget by this record amount. I can't think of a better anniversary present during this, the 50th year of NSF's existence.

I would also like to express very deep thanks to all of you for helping us to achieve this milestone. I am convinced that we did it by uniting and speaking with one voice for all of fundamental research. Every one of you has my heartfelt gratitude. I am especially glad that Sam Rankin has taken the helm at CNSF--the Coalition for National Science Funding. In this spirit of celebration, I would like to share with you not equations, but a short video instead. In a metaphorical way this video segment sums up the sweeping scope of NSF's mission. It is an excerpt from the IMAX film, "Cosmic Voyage," and it takes us on a "cosmic zoom" from quarks to stars. Let's see the video.

[Cosmic Voyage video segment]

[title slide: Innumerable Connections]

The video shows us the innumerable interconnections between the many scales of our universe. It sets the stage for what I would like to talk about with you today. My first theme, as the video segment suggests, is the vital and growing role of the mathematical sciences in all of science and engineering. Then I would like to turn briefly to the interdisciplinary initiatives that have taken shape as prominent features on NSF's landscape. I will spend a bit more time on the newest initiative we intend to propose, which is of course of greatest interest to all of you: our mathematical sciences initiative.

In fact, this is a kind of preview of how we might present our case for the initiative, and we would very much appreciate your advice on the best way to do this beyond the mathematics community.

[Roger Bacon quote over mathematical image]

Roger Bacon observed that "Mathematics is the door and the key to the sciences." For us, seven centuries later, his words ring with even deeper truth.

[MC Escher slide with EO Wilson quote]

A more recent observation about mathematics comes from E. O. Wilson. He writes,"...mathematics seems to point arrowlike toward the ultimate goal of objective truth." Given the accelerating cross-pollination of mathematics and bioscience, it's not a mere coincidence that Wilson is a biologist.

Indeed, mathematics is the ultimate cross-cutting discipline, the springboard for advances across the board.

[a fractal image]

Mathematics is both a powerful tool for insight and a common language for science. Fundamental mathematics engenders concepts and structures that often turn out to be just the right framework for applications in seemingly unrelated areas.

A good example, pictured here, is the fractal, a famous as well as beautiful illustration of how inner principles of mathematics enable us to model many natural structures.

[VLA at sunset slide]

Cosmologists are beginning to draw an awesome portrait of the structure of the universe--using mathematics as the medium. On the other end of the scale, particle physicists begin to sketch quantum phenomena, again with mathematics as their brush and palette. Just as telescopes probe outer space, the mathematical sciences give us a platform to explore hidden universe of the imagination, which mysteriously permeates our real world.

[rocket and neuron]

Newton's invention of calculus inaugurated a new role for mathematics: to enable mechanics to flourish and the physical sciences to thrive. Today, we are watching mathematics empower new areas--biology, neuroscience, information technology, and nanotechnology, as represented by this nerve cell.

[weather prediction]

As we take a quick trip across the disciplines, we find mathematics as a full partner everywhere we alight.
Here is an example from meteorology. We find that computing power at the terrascale, derived from mathematics, gives us the ability to predict storms on a finer scale. The new system reveals violent storms that current prediction systems miss altogether. In this map of Oklahoma, on the left the National Weather Service has missed the storm. On the right the prototype terrascale system predicts the storm.

[El Nino]

On a grander scale, our ability to predict El Nino--the irregular shifts in ocean and atmospheric conditions--is a superb example of where mathematics and computing have brought us. It took the gathering of voluminous amounts of data, and new mathematical techniques to analyze it, to predict the onset of El Nino.

[four hearts]

The meeting of mathematics and medicine augurs well for discovery on many fronts. Mathematics and complexity theory, for instance, give insight into the human heart. The top images are computer simulations of the electrical activity in a normal heart. Below are patterns of fibrillation--uncoordinated electrical activity that leads to heart attack.

This is the work of James Keener--a University of Utah mathematician--and his colleagues, but they go one step further. They are investigating why some patterns of electrical stimulus are better at eliminating fibrillation. People with pacemakers and implantable defibrillators will benefit.

[Sethian body scan]

Here J.A. Sethian of the University of California-Berkeley uses mathematics to isolate and extract individual components from a medical image. In this case we see a two-dimensional cross-section across the chest, with the heart, liver and other features visible. By clicking on the image one can automatically find the outline of whatever region needed, such as the outline of an organ.

[new monkey face graphic made of fractals]

Fractal sets like we see here can be used in computer graphics to build clouds, plants, or the surface of the sea. They are also a goldmine for medical modeling, of lungs or networks of blood vessels.

[metabolic rate graph]

If we look at metabolic rate across the scales of size, we see the order that emerges from a comprehensive view. The rate follows a hierarchy from mammals on the upper right to ever-smaller entities down through a cell, a mitochondrion, and a respiratory complex. We see a suggestion, perhaps, of a universal principle underlying life at all scales.

In fact, Geoffrey West of Los Alamos National Laboratory, who works on this problem, believes there may be two or three hundred such scaling laws for biology. "Tree trunks scale just as an aorta does," he says. "Nature uses the same building blocks at every level."

[fantastic sea creatures derived from knot theory]

As a biologist I find the burgeoning two-way traffic between biology and mathematics especially exciting. I use these fanciful images, in which knot theory gives form to fantastic sea creatures, to symbolize this interchange.
Not only is mathematics revolutionizing biology, but biology begins to foster new paradigms in mathematics. The information science of life edges ever closer to electronic information science. Advances in understanding life may lead to new algorithms and new modes of computing, notably biological computing.

[knot theory and DNA helix]

Another example is knot theory, which gives insight into DNA replication and other molecular processes. Knot theory also has applications to polymer science--the creation of new materials.

[cholera genome]

Here is an application of mathematics to biology dear to my own heart: the elucidation of the cholera genome. I have studied this organism's relationship to its environment for most of my research career. Modern mathematics has helped us reach the brink of being able to predict, for the first time, the onset of cholera epidemics.

The sequencing of the human genome has also drawn upon sophisticated mathematics, and illustrates the onslaught of data we face not only in biology, but also astronomy and elsewhere. NSF's own math division director, Philippe Tondeur, puts it this way: "Data acquisition used to resemble drinking water from a tap, drop by drop. Now it has become more like drinking from a firehose."   Our "post-genomic" era--as a recent Nature [19 Oct. 2000, p. 819] article says--"heralds an encyclopedic era of information about the way biological cells and their genes and proteins behave."

[the five initiatives]

Let's move now to how we implement this vision of "innumerable connections" at NSF. Our mathematics effort really does feed into--and complement--all of the initiatives. It provides the flow of fundamental mathematics essential to the advance of information technology.   It supplies the understanding of complexity and uncertainty critical to sorting out biocomplexity. It gives us some of the tools we need to explore new frontiers at the nanoscale. And math plays an indispensable role in educating the scientific and technical workforce our country needs. Let's take a quick look at each of our initiatives in turn.

[ITR slide]

Our information technology initiative began at the time the report by the President's Information Technology Advisory Committee (PITAC for short) was being prepared. The committee warned that without new federal investment, the United States was in danger of losing its international preeminence in computer science.

NSF is the lead agency in ITR, and we just announced our first round of awards in September. These awards stress "the science in computer science and the information in information technology." Among advances we hope for are software for critical applications like air traffic control; IT to improve science and math education in urban schools; robots to help the elderly at home; and systems to manage massive data files.

[biocomplexity]

Our initiative on biocomplexity seeks to probe both the physical and living realms of our world, and to trace their interconnections. Biocomplexity is a timely perspective because of the growing threats to our environment and the expanding capabilities of our science and technology.

Complexity gives us a perspective spanning all fields and all scales--a richness across different orders of magnitude. We 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 begin to map out the interplay between parts of complex systems. In October we awarded new grants in this multiyear program.

[nano: three scales]

On still another front is our program at the Lilliputian level of the nanoscale, with NSF at the lead of a multiagency effort. These images help us to orient ourselves to this perspective. At the left, you can see an atom, just a few tenths of a nanometer in diameter. In the middle, the DNA molecules are just 2.5 nanometers wide. To the right are red blood cells a few thousands of nanometers wide. At this magical point on the dimensional scale, nanostructures are at the confluence of the smallest of human-made devices and the large molecules of living systems.

We are beginning to manipulate individual atoms and molecules. We're beginning to create materials and structures from the bottom up, the way nature does it. Nanotechnology could change the way almost everything is designed, from medicine to computers to car tires. NSF proposes to focus its nano investment on five interrelated areas. They are: biosystems, nanoscale structures, novel phenomena and quantum control, architecture of devices and systems, nanoscale processes in the environment, and the modeling of multi-scale, multi-phenomena.

[Knowledge the currency of everyday life]

Another initiative is the 21st century workforce. In our new economy, information has moved to center stage, and knowledge has become the currency of everyday life. The long-term goals of this initiative are to generate the knowledge, shape the people, and create the tools needed to develop a workforce second to none. Our workforce must fully reflect the strength of our country's diversity. We will need individuals educated to unprecedented levels of expertise in science, mathematics, engineering and technology.

To date, we have managed quite comfortably by relying on imported talent, but other nations have begun to compete with us. For this new era, we need a highly trainable workforce--and retrainable workforce.

[Nature article headline: "Recognition for mathematics is overdue"]

I'll move now to the role of the mathematical sciences initiative as complementary to the other NSF-wide efforts just described. You may have seen this headline recently in the journal Nature: "Recognition for mathematics is overdue." The editorial about our proposed initiative said that "the whole of science--and society at large--will benefit" from boosting support for math.

[MSI word slide: Why Now?]

It makes eminent sense to replenish the wellspring of fundamental mathematics--without delay. I've already discussed how mathematics has become interwoven with all of science and engineering. However, before mathematical concepts can be applied, they must first be developed. That is why boosting support for fundamental mathematical research is the first component of the initiative.

Fundamental mathematics is also critical to training a mathematically literate workforce for the future. Technology-based industries fuel the growth of our economy, and we need well-trained graduates to fill these jobs. More broadly, as our world grows increasingly complex, the need for mathematical and statistical literacy becomes ever more acute for making good decisions.

[word slide: mathematical sciences in the U.S.]

It's not news to this crowd that our country's world leadership of mathematics is fragile. We've been relying on overseas talent and are not attracting enough U.S. students.

I'll just cite a few figures that buttress the case:

- Between 1992 and 1999, full-time graduate students in math dropped by 21 percent, while U.S. citizens in graduate math dropped by 27 percent.
- In 1997, only 12 percent of fulltime math grad students had research assistantships.

[word slide: mathematical sciences in the U.S.]

Between 1992 and 1999, upper level math majors dropped by 23 percent. In the meantime, NSF's role in support of mathematics is becoming even more important. We provide about two-thirds of federal academic research support, and our share is growing. But our grants in mathematics are small--much smaller than those in other theoretical physical sciences.

[word slide: MSI: Three Frontiers]

Our new initiative in mathematics attacks this situation on three fronts. We propose to advance the fundamental mathematical sciences; accelerate mathematical interchange between the disciplines; and equip our students with mathematical skills and literacy. I'll add that the program is still very much evolving, so the words are subject to change.

[word slide: Fundamental mathematical sciences]

It all begins with strengthening fundamental mathematics and statistics. Again, you know far better than I do the incredible richness of your field. Examples include research on dynamical systems, on advanced statistical methodologies, and on geometry and topology. The slide also indicates how this research would connect with various other disciplines.

[word slide: connections to other science and engineering]

Equally important is to deepen and create new connections between math and other fields. Initially we will emphasize research on:

- managing and analyzing large data sets;
- managing and modeling uncertainty;
- and modeling complex, interacting, nonlinear systems.

[word slide: mathematical sciences education]

The third prong of our initiative is education. It is vital to embed collaborative training in research activities. We also want to step up the professional development of mathematics teachers at every level, and give them the tools they need to communicate the excitement and power of mathematics. Finally, we need research on how people learn mathematics--so we can target our teaching to every student.

[word slide: implementation]

We have identified some mechanisms to reach these goals. It's essential to increase both the size and duration of grants, and expand our support for graduate student and post-docs.
Beyond that, we envision supporting collaborative research groups, new institutes and interdisciplinary centers, and other mechanisms. We seek and we need your advice on these and other mechanisms.

[closing slide: Jovean Bees]

I will close now in anticipation of your questions and comments. We have great hopes for our mathematical sciences initiative, but we have a great challenge before us and can only surmount it by working together. My final slide gives a suggestion of how computing enables us to share some of the beauty of the mathematical world of the imagination--an illustration of how our new tools accelerate the merger of the disciplines, in this case, joining mathematics, computing and art. The work, "Jovean Bees," is by artist Jean Constant, and uses a program by mathematician Richard Palais. To me the work embodies some of those "innumerable connections."

Now I look forward to our discussion. Thank you.