knowledge
wave2003
the leadership forum

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20 February 2003

Presentation to Knowledge Wave 2003 – the Leadership Forum
February 2003

Presentation also available on Forum website - www.knowledgewave.org.nz

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"Crossing ALL Boundaries"
Knowledge Wave 2003: The Leadership Forum
Auckland, New Zealand
February 20, 2003

[Slide # 1: blank slide]

Thank you for the kind introduction, Peter. Distinguished guests, ladies and gentlemen:

I'm honored to speak at the Knowledge Wave 2003 – Leadership Forum. I know this Forum has been and continues to be important to New Zealand's future. Your emphasis this year, on identifying young leaders who will be your navigators in the 21st century, is right on the mark. The economic and social prospects of all nations depend on the knowledge, experience, and foresight of those at the helm. Your commitment to find the best and brightest to lead your nation can only mean great things for the future of New Zealand.

I've had the privilege of visiting New Zealand on numerous occasions, since NSF is responsible for the research stations in McMurdo, South Pole, and elsewhere in Antarctica, with our jumping off point in Christ Church. I'm delighted to be back. Each visit is a reminder of the strong relationship that exists between our nations.

The ties between New Zealand and the U.S. have always been durable and mutually rewarding. Our nations have enjoyed an equal measure of goodwill and cooperation. That includes our scientific endeavors and our ultimate quest for increased knowledge.

Today I am especially pleased to talk about advances in *fundamental* science. The theme resonates deeply for me, both personally as a researcher and as director of the U.S. National Science Foundation, an agency that supports all facets of science and engineering research and education.

Slide #2: [title slide]

I have entitled my talk "Crossing ALL Boundaries" because I want to emphasize two important features of science in the 21st century. First, fundamental research in all fields is one of the pillars of strength and prosperity for all nations. We know that new knowledge spurs the technological innovation that in turn leads to economic growth and improvements in societal well being. It is vital for each nation and for all nations together to purse these goals.

[Slide #3: Knowledge is the currency of everyday life]

There's no question that a new age of discovery, learning, and innovation has dawned. New knowledge is now the principal source of wealth creation and new jobs worldwide. This new, knowledge-based economy has brought lasting changes with profound implications for society. It has transformed the way we live and work, conduct business, and educate our children.

Public investments in fundamental research and education have played a central role in these transformations. So, too, have native intellectual talent and the resourcefulness of the private sector. Taken together, they have made science, engineering and technology enterprise in the 21st century the strongest in history.

Second, a hallmark of such research is that results arise in unexpected places.
Exchange among seemingly unrelated disciplines, often turbulent in practice, can lead to an unexpected harvest of insights. Today I'll illustrate that reality using some particularly vibrant research areas that the National Science Foundation has chosen for focused investment.

Today the boundaries between all disciplines overlap and converge at an accelerating pace. Progress in one area seeds advances in another. New tools can serve many disciplines, and even accelerate interdisciplinary work.

Here is a surprising but illustrative example from astronomy, a science usually seen as offering little practical value.

[Slide #4: adaptive optics: laser guide-star above Keck]

Large ground-based telescopes have their views into space blurred by the earth's shimmering atmosphere. A technique called adaptive optics can correct for the distortion. Here a laser beam creates an artificial "guide star" for the technique.

[Slide #5: Blue Neptune: with and without A/O]

Adaptive optics is an excellent example of unlikely scientific convergence—a striking consilience of astronomy with vision science. The technique sharpens astronomers' vision from ground-based observatories, as we see in these before-and-after pictures of Neptune.

[Slide #6: Cones in eye]

Also a tool for looking into the human eye, adaptive optics produced the first images—shown in red, green and blue--of cone arrangements in the living eye. Fundamental research to create a clearer view of the universe has spawned a new technology for the study of the human eye that could potentially benefit everyone. That's what I'd call a *great* return on our investment!

[Slide #7: word bullet slide: IT, nano, math, biocomplexity]

I will turn now to four technologies that exemplify the power of working across disciplines and the often-surprising relationships we discover when we do so.

These are information technology, nanotechnology, mathematics, and biocomplexity. These technologies have been called the "power tools" of the next economy.

[Slide #8: IBM 650]

Many of you will recognize the next image. It's the IBM 650. I used it for my own Ph.D. research to classify marine bacteria.

I wrote the program to handle what we thought was a large amount of data gathered on *several hundred* bacterial cultures.

This was the first American use of the computer to classify bacteria from the environment. In fact, the coding scheme we developed for bacteriological data remains in use today, and is widely employed in many hospitals across the country.

As for the IBM 650, it was installed in the attic of the chemistry building at the University of Washington, and we graduate students got to use it between the hours of two and four a.m.

Today, an IBM 650 is literally a museum piece. One is on display at the Smithsonian! And as this conference attests, a new age of supercomputing has dawned.

Many of us have seen our work transformed in unimagined ways by the power and breadth of the information and communications revolution that we are all a part of.

[Slide #9: Cholera collage]

My own research on the environmental factors that converge to cause cholera has traveled many miles from the early days of the IBM 650 – to the sequencing of the organism that causes cholera, to handling vast amounts of climate data gathered by satellites, to easy communication with colleagues around the world, particularly those working in countries where cholera is still a deadly scourge.

The changes born of the information age have helped to change the way infectious diseases are understood, and opened new prospects for ameliorating their deadly consequences.

[Slide #10: Terascale computing]

Our new Information and communications technologies help us handle the quantity as well as complexity of data, and enable new ways to collaborate around the globe. Here you see a depiction of the planned teragrid that will link U.S. academic researchers across the nation.

We can collect, store, and manipulate vast quantities of data. We can share those data and communicate new knowledge essentially instantaneously. These capabilities open new doors for collaboration that were unworkable only ten or fifteen years ago.

Soon such connections will link scientists around the globe, instantaneously. That will usher in the true era of international collaboration.

[Slide #11: NSFNet in 1991]

It was only a little over a decade ago in 1991 that NSF opened what was then called NSFNet for commercial use. The rest – the growth of the Internet – is history!

The first wave of the information and communications technology revolution has reshaped the once familiar landscape of the economy and has forced us to clear new paths in research, education, and business. It has swept across every field of research, and changed forever our scientific and educational horizons. New frontiers of knowledge, unimagined only a few years ago, are now open to us.

These tools are also changing the very way we conduct research and creating a new science of the 21st century. When we dramatically advance the speed of scientific research in any area, we give ourselves the mechanism to reach a frontier much faster. Or, better yet, to reach a new frontier that had been unreachable, as well as unknowable.

[Slide #12: Folding protein]

Here is just one example. It takes just 20 milliseconds for a nascent protein to fold into its functional conformation. Until recently, it took 40 *months* of computer time to simulate that folding. With new terascale computer systems – operating at over one trillion operations per second – we have reduced that time to *one day.* That’s 1000 times faster.

[Slide #13: nano collage]

These images portray yet another emerging frontier. They look as if they came from the brush of an artist dabbling in abstract expressionism, but all are actually glimpses of discoveries at the nanoscale.

At the dimension of the minute, the very small, matter behaves in mysterious ways, with staggering possibilities to transform our larger world.

Progress in many disciplines converges at the nanoscale. This is the magical point at which the worlds of the living and non-living meet.

[Slide #14: nanodumplings]

Nano systems may indeed transform drug delivery. An example is the "nanodumplings" pictured here--tiny spheres that mimic living entities, such as viruses, by their shape and size.

Engineered to avoid detection by the immune system, they show excellent promise for delivering drugs directly to a target site, or for gene therapy.

They could also be used to scavenge unwanted substances, whether "bad" cholesterol from the body or pollutants from the environment.

[Slide #15: Polystyrene particles]

At the University of Pittsburgh, Gilbert Walker and his team are investigating how the topography of an artificial surface influences where cells bind, and how the resulting distribution influences the way they communicate.

[Slide #16: nanobiogeo]

The slide shows 100-nanometer polystyrene particles bound into the grooves of a “no-stick” surface. By studying how textured polymer surfaces organize particles that are deposited on it, we can learn some of the fundamental reasons for the failures of implants, such as artificial vascular grafts.

[Slide #17: math networks]

Another new frontier: fundamental mathematics. It engenders concepts that often turn out to be just the right framework in seemingly unrelated areas.

Here the fractal concept--called *the fingerprint of Nature*--holds firm across scales and fields. We see a river drainage network, the network of a leaf, and even a painting by Jackson Pollock – all of which reflect the statistics of chaos. Fractal sets are also a goldmine for medical modeling--of lungs or networks of blood vessels.

[Slide #18: E. O. Wilson Quote on mathematics]

This discussion would not be complete without mentioning mathematics. Mathematics is at once the language of science and engineering and a tool for progress. Much of the research I’ve highlighted has benefited from advances in fundamental mathematics that have applications in a broad range of fields.

[Slide #19: Fruit fly figure-of-eight wing pattern]

A recent example is the work of mathematician Jane Wang at Cornell, who has produced the first concrete explanation of how some insects can manipulate the flow of air around them so as to switch in an instant between darting motions and hovering stillness. These erratic motions are like those that cause a piece of falling paper to tumble and flutter. They are produced by vortex wakes. Wang’s mathematical theory explains how the rotating motion of insect wings during flapping first creates then “sheds” or “casts off” these chaotic wakes, allowing an insect to hover.

The lessons we learn from insect flight will shed new light on a wide range of systems – from building insect-sized micro-air vehicles, to understanding the rising of bubbles in fluids. There is no doubt in my mind that this solution to an extremely complex problem in fluid dynamics will soon find a host of applications in the biosciences.

[Slide #20: biocomplexity spiral]

My fourth emergent area is biocomplexity, a term I have coined to describe the study of the complex interactions in biological systems, including humans, and between biological systems and their physical environments.

We know that ecosystems do not respond linearly to environmental change. We also know that understanding demands observing at multiple scales, from the nano to the global.

[Slide #21: Chagas]

The ecology of infectious disease is one important focus for biocomplexity studies. A good example is work on Chagas disease, an infection caused by a protozoan parasite and a disease that afflicts rural populations of Latin America.

We see the parasite, *Trypanosama cruzi*, in an infected droplet of blood.

Using a mathematical model of all inhabitants of a village house—the humans, dogs, bugs--researchers were able to show that keeping infected dogs out of human sleeping areas greatly reduced the incidence of this debilitating disease. Insight emerged only after the ecology had been unraveled.

Genomics offers unprecedented opportunity to begin to probe a microbial world that is almost a complete mystery.

The report pictured here stresses that "Genome-enabled microbial research holds enormous promise for understanding life at its most basic level."

[Slide #22: Richard Lenski: digital and bacterial evolution]

In another merging of worlds under the biocomplexity rubric, a microbiologist, Richard Lenski at Michigan State, has joined forces with a computer scientist and a physicist to study evolution in action, using two kinds of organisms--bacterial and digital.

Here the two foreground graphs actually show the family tree of *digital* organisms evolving over time. On the left, the digital organisms all compete for the same resource, so they do not diversify and the family tree does not branch out.

On the right, the digital organisms compete for a number of different resources. Deep branches develop in that family tree over time.

In the background are round spots--actually laboratory populations of the bacterium, *E. coli*, which also diversified over time when fed different resources. Biocomplexity brings insight to the *in vivo,* even when drawn from the *in silico.*

Now let's look at an example of how an organism shapes the physical environment.

[Slide #23: Banfield – yellow biofilm]

Led by Jillian Banfield, now at UC-Berkeley, and a team at the University of Wisconsin, this work looks at a complex environment: an abandoned and flooded mine. We see biofilms here that live on the floors of the flooded tunnels. The goal of the work is to understand geomicrobiological processes from the atomic scale up to the aquifer level. Acid drainage from such mines is a severe environmental problem. At one mine being studied, workers accidentally left a shovel in the discharge; the next day half the shovel was eaten away by the acid waste.

[Slide #24: Banfield – blue and yellow sulfur balls]

We search for ways to remediate the damage in areas like these. The microorganisms in the biofilms play a surprising role. For one, they can clean the zinc-rich waters to a standard better than that of drinking water. At the same time, bacteria in the biofilms are depositing minerals on the tunnel floors. The yellow balls are aggregates of tiny zinc sulfide crystals just 2-5 nanometers in diameter, formed in very high concentrations by the activity of microorganisms. The work sheds light on an environmental problem, while giving insights into basic science with economic benefit: we are learning how mineral ores of commercial value are formed.

Researchers are studying this system on a number of scales -- from the early evolution of life on earth to the nanoscale forces operating inside the microorganisms and in their immediate environment.

[Slide #25: NEON map]

This is NEON--the planned National Ecological Observation Network--a schematic portrayal of an array of sites across the country furnished with the latest sensor technologies.

The same themes emerge--research collaboration across great distances, shared instrumentation, and integrating across a range of scales--in both the physical and biological sciences.

[Slide #26: instrumenting the environment]

Here's an imaginative rendition of a NEON site fully instrumented (with apologies to the artist Rousseau). Networks such as NEON require state-of-the-art sensors of every kind.

Such a site will measure dozens of variables in organisms and their physical surroundings. This, in fact, is a biological "early warning system."

High-capacity computer lines will link all the sites, and the entire system will track environmental change from the microbiological to the global scale. A network such as NEON can also serve to monitor invasive species or disruptions from an attack of bioterrorism.

[Slide #27: Tree of Life]

This has been just a sampling of new research with multifaceted implications for society--for our security, our economy, and our future.

We glimpse the unity underlying research, and the need to weave together our efforts.

The "Tree of Life" we see here--a project to construct a universal tree for all 1.7 million named species of living organisms--represents that new mindset.

Just as integral to our progress is yet another dimension of the complex kaleidoscope of science and engineering today.

No matter how spectacular the research frontier, we need to make yet another connection--not just across the disciplines, but in a linkage with the public.

We have the obligation to convey the excitement of research as well as basic scientific knowledge to strengthen the society that surrounds and supports us.

Both our economy and our well being depend upon this outreach, more urgently now than ever before.

Scientific literacy so often begins with a spark of excitement, which can be kindled in childhood or even as an adult. It's been said that "we do not know how we know," but that is beginning to change.

[Slide #28: Where Discovery Begins]

What does all of this mean for us as scientists, innovators, and entrepreneurs? It has become our task to cross boundaries and collaborate, to respond to the emerging complexity of science and engineering and its next generation of discoveries.

I believe we are in the midst of a new age of exploration and discovery that has already produced extraordinary new knowledge. And we are on the threshold of even deeper more fundamental insights about our planet and ourselves.

A great challenge today is to sustain the momentum of discovery and realize the progress that our new tools promise.