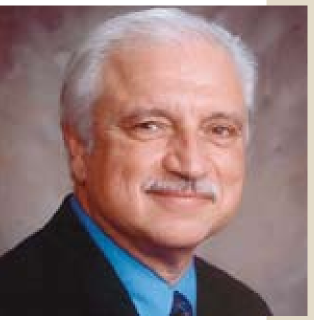
a foundation for the advancement of science Research Corporation

Annual Report 2005

Table of Contents

President's Message

As I contemplate completion of my first year as president of Research Corporation, I remain humbled by the confidence placed in me by the Research Corporation Board, and excited, enthused and exhilarated by the prospects for the future. As the second oldest foundation in the United States, Research Corporation has a long and proud tradition of funding innovative science and fostering science education. Such a tradition is the springboard to finding ways through which Research Corporation can best continue to catalyze scientific research and education in a future that will require multifaceted approaches to address increasingly complex questions.



This past year has been dominated by strategic thinking and planning. In addition to working with members of the Research Corporation Board and our Science Review Committee, two Presidential Panels (for rosters see http://www.rescorp.org/initiatives.php) have provided expertise and insight into issues that we need to address for the future.

On the national level, while Research Corporation's reputation as a foundation that funds cutting-edge science remains strong, the reality is that the $7.5 million in funding in 2005 makes us a small foundation when compared with the overall monies for science and science education provided by the federal sector as well as by many larger private foundations. My personal vision is that Research Corporation must be the "tip of the funding spear" rather than merely another "bucket of water" in a large river of resources. Therefore, how a small foundation such as Research Corporation targets its resources is of critical importance. As a small foundation with a history of taking risks, we can take advantage of our comparative lack of complex infrastructure that often immobilizes larger funding organizations, and thus more easily and quickly find ways to provide funding for innovative, emerging areas of research that would otherwise fall through the seams of traditional funding mechanisms. By doing so, we can provide critical resources that can, like the "tip of a spear," open new areas of study that will ultimately gain the attention and resources of larger agencies and foundations (thus the full "weight" of the spear behind the tip). Therefore, our strategic thinking and planning efforts are crucial to developing the wisdom, insight and agility necessary to sustain the leadership role in science that Research Corporation has deservedly earned over its ninety-four years of existence.

I look forward to this next year, and the years to follow, with the enthusiastic anticipation of seeing Research Corporation build upon its historic mission to leverage a new future for scientific research and education.

James M. Gentile

Something there is that doesn't love a wall,
That sends the frozen-ground-swell under it,
And spills the upper boulders in the sun,
And makes gaps even two can pass abreast.

— ROBERT FROST, "MENDING WALL"

Interdisciplinary Research: Opportunities, Obstacles and Options

by Randy Wedin

Flip through a college course catalog, amble through the stacks at a science library or eavesdrop on an animated conversation among graduate students at the local coffee shop. It quickly becomes apparent that science is organized by discipline.

Each discipline represents an intellectual territory—a field—where scientists harvest data, information and knowledge. And just like the farmers in Robert Frost's native New England, scientists have organized their territories by building walls and fences between the fields, between the disciplines.

Are these fences useful? Are these walls necessary? What are the advantages and disadvantages of organizing science along disciplinary lines?

Although Isaac Newton famously claimed that science progresses by standing on the shoulders of giants, it's equally true that science advances by standing on the shoulders of disciplines. The organization of science along disciplinary lines is one of the keys to its success.

The disciplines provide an effective structure for transmitting knowledge from one generation to the next—for passing along a body of information and for teaching students how to "do science." Within a discipline, students learn a language, a culture, and a whole set of unwritten rules. A discipline provides a "home" where like-minded individuals can exchange information, work together, practice their profession, and encourage each other in a shared enterprise toward common long-term goals. Over time, the discipline begins to take on a life, character and mystique of its own.

Clearly, the benefits of organizing and structuring human effort by field and discipline are many. As pointed out by one of the farmers in Frost's poem, "Good fences make good neighbors."

And yet, science also advances by studying problems, by looking closely at nature, by asking questions which lie outside predetermined boundaries. It also advances by peering beyond disciplines and by looking deeply into the interfaces between them. As the second farmer points out in Frost's poem, "Something there is that doesn't love a wall."

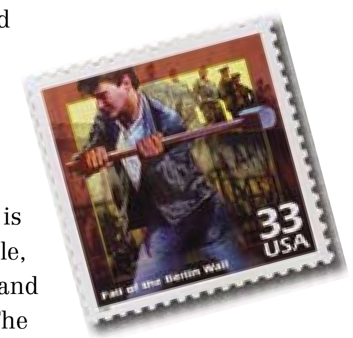
John Hildebrand, a professor of neurobiology at the University of Arizona, says, "As I tell the students every year in my undergraduate class, Mother Nature doesn't know about chemistry, physics, mathematics and molecular biology. It's all one glorious thing to Mother Nature."

Strength and satisfaction come from mastering one discipline and advancing that discipline to the next level. But surprise and joy come from finding connections between two disciplines, from asking and answering questions that lie outside established fields.

Science and society need both. They need disciplinary teaching and research. And they need interdisciplinary teaching and research.

While fully acknowledging the power and importance of disciplinary research, the focus of this article is interdisciplinary research. It's an approach to research that's becoming increasingly important. It's an approach to research that's made possible, ironically, because of the strong scientific foundation and many new technologies that have grown out of discipline-based research.

Interdisciplinary research, however, is not an easy activity to undertake in a world built on disciplinary structures. This article discusses some of the many barriers and impediments to interdisciplinary research. Then it looks at innovative ways that individuals and organizations are circumventing those barriers, dismantling those fences, and breaking down those walls.



Opportunities for interdisciplinary research can be found at interfaces between many different disciplines. For example, nanotechnology research is flourishing at the interface of physics and chemistry. And in another example, scientists working with the very big and with the very small—cosmologists and particle physicists—are exploring common ground in the quantum realm. The barriers and options discussed in this article apply generally to interdisciplinary research in all areas of science.

One interface where the challenges and opportunities for interdisciplinary research are especially abundant is the interface of the physical sciences and the life sciences. This article will focus on that particular interface, because many scientists believe it's an interface of very rich scientific potential today. It's also the interface where solutions to many of tomorrow's important problems are likely to be found.

The examples, opinions and insights discussed in this article are based on interviews with fourteen scientists, many of whom have been especially active in interdisciplinary research. A number of recent articles and reports—from the National Research Council, the National Science Foundation and the National Institutes of Health—have also proven very useful. A full bibliography of these sources is available at the Research Corporation website, www.rescorp.org.

Opportunities at the Interface

The history of science abounds with examples of scientists who made great advances by working in more than one discipline, integrating knowledge as they went. Isaac Newton, in the seventeenth century, did research in mathematics, optics and mechanics (and alchemy, too). Louis Pasteur, in the nineteenth century, started his career as a professor of chemistry, worked on practical questions related to wine spoilage and diseases, and eventually laid the foundations of microbiology and immunology.

In the twentieth century, James Watson (trained as a zoologist) and Francis Crick (trained as a physicist) worked as an interdisciplinary team to unravel the genetic code encrypted in DNA. Interestingly, a number of the scientists who helped establish the field of molecular biology in the mid-twentieth century were, like Crick, originally trained as physicists.

Today, at the beginning of the twenty-first century, many highly creative scientists are also interdisciplinary. A 2005 National Research Council (NRC) report, *Facilitating Interdisciplinary Research*, estimates that two-thirds to three-fourths of MacArthur Fellows in science (recipients of so-called "genius awards") work in interdisciplinary fields.

Interdisciplinary research advances not only basic science but also applied science. In recent decades, interdisciplinary teams of scientists and engineers have been responsible for responding successfully to national needs and societal challenges. Examples include the Manhattan Project, Project Apollo, and the Human Genome Project.

Looking ahead to the next several decades, many scientists believe that great opportunities for scientific advancement lie at the interface of the life sciences and physical sciences.

Kenneth Keller, a chemical engineer and former president of the University of Minnesota, points out that many scientists and engineers originally trained in the physical sciences are turning their attention toward the biological sciences. "These are extraordinarily interesting and complex problems. If the most important aspect of the frontier of science is the 'rate of change' of knowledge, not the 'level' of knowledge, then the biological sciences are where it's at."

"If you look at physics today," continues Keller, "it's extraordinarily sophisticated. We have gained enormously in the last hundred years. But the rate of change of knowledge in physics, I would argue, is not nearly as great as the rate of change of knowledge in the biological sciences. That's in part because the biological sciences started later to become quantitative, and the physicists had already made great gains in the first half of the twentieth century."

In a complementary way, scientists originally trained in the life sciences are finding more and more points of overlap with the physical sciences. *Facilitating Interdisciplinary Research* agrees, "Today, the computational and statistical power of mathematics and the research facilities of the physical sciences are required for making sense of, for example, genomics, proteomics, epidemiology, structural biology and ecology."

The potential and excitement at the interface of these disciplines have even reached the halls of Congress. The House Appropriations Committee included this language in its report accompanying the FY2004 Authorization for the National Institutes of Health (NIH):

"Increasingly, the boundaries between the life sciences and physical sciences are being blurred, as capacities and talents bridging the disciplines are essential for modern experimentation and discovery. Accordingly, the Committee believes that a major effort must be undertaken to promote the advancement of research at the interface between the life sciences and the physical sciences." (House Labor/HHS Appropriations Subcommittee–Report 108-188, p. 94)

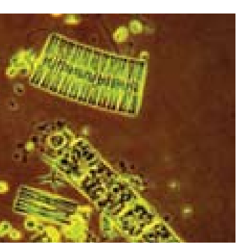
In a flurry of meetings, conferences and reports over the past two years, groups of scientists and administrators from academe, government and industry have debated, listed and prioritized the opportunities and challenges at the blurred boundaries between the life sciences and physical sciences.

Participants in the "NSF Workshop on Molecular Basis of Life Processes (2004)" organized their conclusions into five "Grand Challenges":

- Chemistry to see and steer biology
- Cellular senses and decisions
- Supranatural chemistry: designing and synthesizing artificial cells that capture the essence of their natural counterparts
- Materials biology
- Molecular theory of life

Participants in the "Conference on Research at the Interface of the Life and Physical Sciences: Bridging the Sciences (2004)" arranged the opportunities into a different configuration, listing these seven areas:

- Large-scale global problems (including climate change, national security, complex diseases, emerging diseases, environmental remediation, energy production and distribution, and food production)
- Healthcare in the twenty-first century
- Multi-scale phenomena
- Molecular-level measurement tools
- Predictive understanding of biological systems
- Biological complexity
- Integrating biological and physical systems



From these lists, it's clear that the opportunities are many and the challenges are great. And in the months since the conference reports were published, scientists working at the interface have continued to uncover new opportunities—and the global problems have only increased in magnitude.

While this article focuses on interdisciplinary research at the interface of the physical and life sciences, the barriers and options mentioned here apply equally well to other interfaces. Demanding challenges and rich opportunities for interdisciplinary research can also be found at interfaces such as nanotechnology and materials (the interface between chemistry and physics) and cosmology and quantum physics (the interface between astronomy and particle physics).

This article won't try to summarize or review the scientific content of these many interdisciplinary research areas. Instead of further discussing the "content" of interdisciplinary research (i.e., the specific areas of research being studied and the specific societal problems being addressed), this article will look at the "process" of interdisciplinary research. What are the barriers to interdisciplinary research? And what innovative options are available for overcoming these barriers?

…creativity in science, as in the arts, cannot be organized. It arises spontaneously from individual talent. Well-run laboratories can foster it, but hierarchical organization, inflexible, bureaucratic rules, and mountains of futile paperwork can kill it. Discoveries cannot be planned; they pop up, like Puck, in unexpected corners. — MAX PERUTZ

Barriers: Existing Institutional Structures

The existing institutional structures that have evolved to serve the disciplines form one of the most significant barriers to interdisciplinary research. These structures are found throughout the scientific community—from individual academic departments to international scientific societies to peer-reviewed journals.

James Serum, a chemist and manager with Hewlett Packard for over twenty-five years, has spent most of his career in industry, but he's also spent much of his career involved in science education, including being a member of the Council on Undergraduate Science Education (CUSE). From this vantage point, he observes, "The departmental structure by discipline has had a huge impact. Each department focuses on a subject from the purity of its own discipline, whether it be physics, chemistry or biology. It's a significant barrier, although I see lots of places where there is a significant effort to overcome these barriers. Over the course of my academic involvement, what was really evident was the resistance by departmental faculty to focus on something other than their own discipline, to think outside the box. They aren't often incented to do that."

Keller says, "The university disciplinary structure organizes research around departments, and there is a tyranny of disciplines. It's very difficult for anyone to take ownership of work that is between departments."

Hildebrand describes the disciplinary barriers as the "guild mentality"—"There's a problem in colleges and universities, and it's the same problem we encounter with funding agencies. They're always organized around departments, panels or units that are discipline-bound—such as physics or chemistry or molecular biology. There are very few exceptions."

"Over time, a guild mentality tends to build up," continues Hildebrand. "The molecular biologists, for example, see themselves as defending the turf of molecular biology. They don't want to see resources bled away from them to support evolutionary biology or ecology. Although it's all biology, they see those areas as outside their guild and away from what they think is the center of the universe."

Hildebrand says, "The departmental and disciplinary structure was created as a convenient way to organize curricula, distribute paychecks and allocate space. Universities, for hundred of years, have created these focus areas that then emerge as disciplines. It never did make intellectual sense in my opinion."

The views of Serum, Keller and Hildebrand—that existing institutional structures such as the academic department are important barriers to interdisciplinary research—were echoed by nearly all the scientists interviewed for this article. Similar results were found in a survey conducted for the National Research Council's Committee on Facilitating Interdisciplinary Research. When asked if there were impediments to interdisciplinary research at their own academic institution, over 70 percent of the respondents answered "yes."

The disciplinary nature of science is not only found on college and university campuses. It's also reflected in the wider world of science–whenever and wherever scientists gather. Whether in scientific societies, journals or funding agencies, longstanding disciplinary barriers are firmly in place. And new barriers arise as fast as interdisciplinary fields coalesce, take shape, and evolve into disciplines.

Scientific societies provide a home where the disciples of a discipline can share information. Societies sponsor meetings, publish peer-reviewed journals, recommend curricula, and recognize outstanding achievement through awards programs. According to the National Research Council, the number of scientific societies in the United States grew from 82 in 1900 to 367 in 1985. The Scholarly Societies Project at the University of Waterloo (www.scholarly-societies.org) provides website links to nearly 3,000 scholarly societies around the world in scientific, engineering and medical subjects.

Just as the number of scientific societies is burgeoning, so too is the number of scientific journals. The Institute for Scientific Information (ISI) covers 8,700 international journals in its database. Nearly all of these journals cover a narrow slice of a discipline, with authors, reviewers and readers all coming from that one discipline or subdiscipline. (It's interesting, however, to note that several of the most significant journals, such as *Science* and *Nature*, cut across the disciplines.)

When a wall is collapsing, everybody gives it a push — CHINESE PROVERB

The creation of new societies and new journals is a double-edged sword. On the one hand, it demonstrates the vitality of the scientific enterprise. Arthur Ellis, division director of chemistry at the National Science Foundation, says, "The nucleation phase of an interdisciplinary field can be catalyzed by workshops and conferences that bring together researchers from existing disciplines. Evidence that an interdisciplinary field has been established can include new academic structures, professional organizations, and scientific journals, as well as identifiable support from funding agencies."

On the other hand, scientists have a finite amount of time to spend attending conferences, reading journals, and developing new contacts. The rapid increase in these specialty conferences, societies and journals makes it increasingly challenging for scientists that want to move freely across disciplines.

The barriers that exist between broad disciplines—such as between the physical and life sciences or between chemistry and physics—are also often found between subdisciplines.

As the body of scientific knowledge has grown, both in breadth and depth, it's been necessary for the departmental structure and disciplinary structure to evolve. Within chemistry departments at large universities, for example, there are sub-departments, such as physical chemistry, organic chemistry, inorganic chemistry, and analytical chemistry. Even between sub-departments, the barriers arise.

Geraldine Richmond, professor of chemistry at the University of Oregon, says, "Breaking down barriers between departments at some institutions is easier than breaking down disciplinary barriers within departments—in chemistry, in particular. For example, many physical chemists have stronger interactions and collaborations with physicists than with their organic colleagues. This stovepiping within chemistry is exacerbated in departments that are territorial about their curriculum, where faculty of a certain discipline are restricted to only certain courses. Whereas in physics, many faculty teach across the curriculum. Such bizarre territorial behavior goes on in some of our best chemistry departments that I often think we need to bring in therapists."

Hildebrand observes a similar situation in the field of biology. "Within biology departments, there's a big schism between reductionist biology (such as molecular biology, genetics and genomics) and organismal biology (such as evolutionary biology, behavioral biology and ecology). If you look at universities around the country, you'll find very few that still have an integrated department of biology. Usually they've split into at least two, and sometimes more, departments. It's a combination of a discipline-bound view of the world and a trench mentality to protect your guild. It's very unimaginative. I find it very disappointing that people behave that way, even if I partly understand why they do it."

With all these barriers—between departments, fields, disciplines, even subdisciplines—the system can be daunting for anyone interested in interdisciplinary research.

Barriers: Tenure and Promotion Criteria

In a recent survey conducted for the NRC Committee on Facilitating Interdisciplinary Research, respondents were asked to identify the top impediment to interdisciplinary research at their institutions. The top impediment, listed by both individual researchers and by provosts, was "promotion criteria."

In particular, the issue of tenure criteria is critically important. For junior faculty moving towards tenure, the risks of engaging in interdisciplinary research are very real.

Keller says, "To get the kind of credibility you need to be promoted and to get grants, you have to be pretty deeply embedded in your own field. That works against people who operate across disciplinary boundaries. A young person in a department who chooses to go into one of these interdisciplinary fields has difficulty finding funding and difficulty making a reputation in the field that would warrant their ultimate promotion."

A number of the scientists interviewed for this article said that one of the major issues in the tenure review process is the challenge of identifying an individual's contribution to projects that are collaborative in nature. This problem affects all scientists who engage in collaborative projects, including those who partner within their discipline. However, it's an especially acute problem for interdisciplinary research, because nearly all interdisciplinary projects involve collaboration, often engaging faculty in other departments and disciplines.

John Hopfield, professor of molecular biology at Princeton University, says, "University promotion and tenure are based on recognized accomplishment of individuals. University professors are expected to 'run their own shows.' At typical universities, if there's cooperative research between two faculty members, each of them gets half the credit. At Bell Laboratories [an institution with which Hopfield had a long-time association], each of them would have gotten full credit. Bell Labs was a marvelous place for getting three people to do one thing which none of them could have done alone. And universities just do not work well, at least historically, in that mold."

Hopfield continues, "Times are changing somewhat, but the evaluation procedures of faculty still militate against collaboration. And it becomes exacerbated if the research is between departments. There's very much, in universities, a feeling of 'our department' and 'our discipline.' Things which involve cooperation with other disciplines have historically been suspect. Princeton, for example, is only in the last two decades managing to get away from total insularity of isolated departments."

Thomas Cech, 1989 Nobel Laureate in Chemistry and president of the Howard Hughes Medical Institute, identifies the same issue. One of the most important barriers to interdisciplinary research, he says, is "the reward structure at the American research university in terms of authorship, recognition, promotion and tenure. If someone is a vibrant, critical part of a project, they might end up being middle author on a lot of their papers. If they do not yet have tenure, this almost always ends up being a problem with their promotion. People say, 'They're just a cog in a wheel. They're not driving this project. Where's the evidence of their independence? Before we give someone tenure, we want to make sure that they are self-sufficient and are able to lead projects, not just follow.' It happens over and over and over again."

Facilitating Interdisciplinary Research highlights several additional challenges faced by an interdisciplinary faculty member seeking tenure. Publications that are not recognized as being in the home department's discipline are likely to be valued less than those publications residing comfortably within disciplinary bounds. Other activities, including interdisciplinary teaching and service to the academic and scientific communities, are also likely to receive less value when they fall outside the bailiwick of the tenure-granting department. Coadvising students across departments can be difficult or discouraged by institutions, and these pressures can discourage student advisees and thus faculty members' own research productivity.

Efforts by the tenure evaluation committee to judge the overall quality of the scientific work are more challenging when that work falls outside the expertise of the committee members. Letters from outside reviewers that adequately explain the importance of the work, especially those from reviewers residing in non-equivalent departments, may receive less weight in the evaluation guidelines.

Interdisciplinary research often takes longer than disciplinary research, yet not all institutions recognize or allow for this. Startup times to arrange equipment, staffing and infrastructure; development of a network of contacts; acquisition of funding; mastery of two "languages" and "cultures"—all these activities require extra time. And if the tenure clock is ticking, this may be time that a junior faculty member can ill afford.

While the barriers imposed by each of these individual challenges might be relatively small, the "accumulation of disadvantage" can be considerable over the course of a pre-tenure career. Recognizing the harsh reality of today's tenure and promotion situation, some senior scientists who are strong advocates for interdisciplinary research are hesitant to encourage young faculty to pursue it.

Keller says, "In the early stage of a field, you can't expect the young people to be the pioneers, because they are the most vulnerable. The ones who are more likely to bridge the gap and to create the new structures that can sustain the young people moving into the field are the people already very established in their field. They're not at risk. They're the ones that can really reach across disciplinary boundaries and create the structures that would support young people in the future."

Barriers: Education and Training

The interdisciplinary researchers of tomorrow are being educated and trained today–or are they? Does the current discipline-based system of education and training provide a good environment for nurturing the scientists of tomorrow?

(Many of the serious issues of science education—including issues such as K-12 science/math education; scientific literacy of the public; competitiveness and economic growth; changing demographics and the diverse workforce of the future—are beyond the scope of this article. While Research Corporation is interested in these subjects, this article focuses on the aspects of education and training related specifically to the question of facilitating interdisciplinary research.)

On most college and university campuses today, courses and degree programs—both undergraduate and graduate—are organized within departments. However, as Hopfield points out, "the structure of most universities is based on the nineteenth century disciplines." There is, therefore, a serious mismatch between science as it is taught and science as it is practiced. While the curricula at these academic institutions have definitely advanced beyond the nineteenth century and well into the twentieth century, many scientists believe the curricula are seriously outdated for today's and tomorrow's needs.

Two years ago, Gregory Petsko, professor of biochemistry and molecular pharmacodynamics at Brandeis University, published a provocative essay calling for an interdisciplinary curriculum to replace today's outmoded chemistry curriculum ("Bad Chemistry," *Genome Biology,* 2004, 5:102). Petsko, who was trained as a chemist, wrote:

> "I don't see how [building a strong interdisciplinary biology curriculum that includes physical science, information technology, and mathematics] can ever happen as long as college chemistry in general, and introductory chemistry and organic chemistry in particular, remain the way they are now. It isn't just that some of the so-called essential 'basic' material really isn't all that essential to most of the students, or to what other chemistry they will need to learn later. It's also that the examples used to motivate students to learn those topics that really are essential are dull, irrelevant, and archaic. In general chemistry courses today, just like forty years ago, a week or more is spent teaching gas laws, but blood gases are almost never mentioned. Another week or more is often devoted to nuclear chemistry, but seldom in the context of the use of radioactivity in biology (radiocarbon dating is the favorite example these days). Electrochemistry is given several weeks of instruction, but not in the context of electrophysiology, which is the one place where it really will matter to most of the students in the class."

Petsko says, "I thought I'd get some flak in response to the article, but I only got positive comments. It may be that chemists didn't read the article, but I think most people understand the truth of it."

A similar indictment can be brought against introductory physics courses. José Onuchic, professor of physics at the University of California at San Diego, says, "First-year physics and chemistry courses haven't changed for fifty years. We are missing a lot of exciting new science. Freshman courses are horrible—an absolute disaster—in terms of exciting people to do science. So the students don't do science because of the course, they do it in spite of the course."

The problem of narrow specialization and segmented curricula found in undergraduate courses is too often perpetuated in graduate school. Serum says, "The training for specific expertise can act as a barrier, because the entire training of expertise is usually by discipline. It's true at the undergrad level, but the narrow focus is even worse in grad school. An example is a person, trained as a biologist, who in today's world needs to use computational skills in order to advance the understanding of the problem—and yet they're not trained that way."

"Specialize if you want," says Petsko, "but remember that today's hot field is tomorrow's routine tool. Highly specialized people doing highly specialized things are always valuable. But I believe the future of biology is going to be for the generalists. The highly specialized people are going to do very important and interesting work, but the frontiers of the field are going to be pushed by people who are more broadly trained. So it's a question if you want to be a leader or not."

Randall Murch identifies another major problem with the narrow focus of today's educational system. Now the associate director for research program development in the Office of the Vice President for Research at Virginia Polytechnic Institute and State University, Murch spent most of his career at the Federal Bureau of Investigation. "When I was head of the FBI's Engineering Division, I noticed that we had bright, young graduates—primarily at the B.S. and M.S. level—who were all well schooled in rote learning or 'book learning.' They could tell you on which page of a textbook to find the answer, and if it was an equation-based answer, they could probably recite the equation. But they didn't fundamentally understand how to apply that in a problem-solving context."

In order for students to move seamlessly into this type of work, Murch believes "some training and some experience in problem-oriented research or applications is critical for students. And if that's the case, faculty will have to be trained in that approach, because most faculty do not come from government or industry."

Whether the interdisciplinary research occurs in academe, government or industry, the scientists involved in collaborative projects are sure to find themselves facing a major barrier—communication across disciplinary barriers.

Barriers: Communication

When young scientists emerge with their Ph.D. degrees, after being immersed for five or more years in discipline-based graduate programs, they think, talk and intuit like chemists, biologists or physicists. And just like residents of separate countries with distinct languages, customs and beliefs, they find it difficult to communicate with each other.

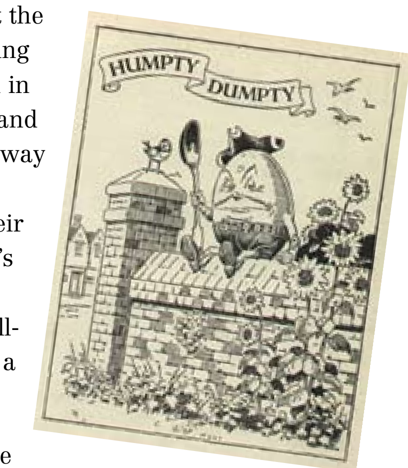
Sometimes the communication difficulties are caused by trivial differences in jargon and terminology. "When discussing my field of x-ray crystallography," says Petsko, "physicists talk about 'kilo electron volts' and chemists talk about 'wavelength.'" A "cell" means different things to a physicist (e.g., fuel cell), a chemist (e.g., unit cell) and a biologist (e.g., stem cell).

However, communication difficulties are often much more profound than simple vocabulary issues, resulting instead from the very way in which scientists frame problems, questions and solutions. According to Petsko, "Physicists are trained to use Occam's Razor, and to think about beauty and simplicity. Occam's Razor never works in biology; biologists don't care about 'beauty.' It's hard to learn these differences if you didn't grow up in the field. Unless you were trained in both fields from the beginning, you're always going to be an amateur in one of them."

Nancy Kopell, a mathematician and co-director of Boston University's Center for BioDynamics, offers this example based on her experience collaborating with both mathematicians and neuroscientists. "People who get a degree in mathematics learn to think in a certain mathematical way—you're interested in generalizations, abstractions and a big broad overview. Certain kinds of logical details matter a lot to you: Does x follow from y in all circumstances?"

"On the other hand," continues Kopell, "if you're a biologist, you're used to thinking in terms of what facts do I know? What are the experimental conditions? What's the context in which something is true or not true? You care about the fact that 'a rat is not a mouse is not a ferret is not a cat.' All the things that get lumped together by mathematicians who might think 'a brain is a brain is a brain is a brain' become extremely important to neuroscientists. So learning those different cultures is an enormous barrier. You can read and read and read, but where will it get you in terms of being able to ask a good question?"

Kopell says, "Training is critical and still not done at a scale that's necessary to really encourage interdisciplinary interactions. It's helpful if people learn to speak several languages while they're still young. And for science, the critical period isn't when you're five years old, it's more or less when you're in college and graduate school. Beyond that it gets harder. So it's very important to have training programs in which people, as a matter of course, are exposed to different scientific cultures and just 'take them in as mother's milk' –just like they would take in a single culture if they were getting a straight Ph.D. in one area. Once they're assistant professors and have learned to think in one way—and one way only—it gets much, much harder."



Joaquin Ruiz, professor of geosciences and dean of the College of Science at the University of Arizona, says, "There's no doubt that right now we're all putzing around at the edges of our own disciplines, but in fact we were all educated in our own disciplines. You acquire an intuition when you're getting a degree and after many years of doing something. Trying to move into a field that's far away is very difficult. For example, there is no doubt that mathematics is hugely important for biology. But the people who are doing that today have had their degree in one or the other of the disciplines. You don't have somebody who's gotten their degree both in mathematics and in biology, which means not only that they understand both languages very well but that they have a well-established intuition that comes from dealing with those two disciplines for a long time."

Even when everyone agrees that communication across disciplines would be a good idea, two obstacles present a huge challenge: time and space.

Effective communication takes time and patience, both rare commodities in today's world. Ruiz says, "In the end, it's a bunch of really busy people who have to make time for these things. It's very challenging to find time for new things because of their many commitments."

Cech points to the physical separation between the relevant departments as an important barrier to interdisciplinary research. "Very often, physics and chemistry departments are not in the same building as biology. In many cases, the medical school can even be in a separate city. And engineering colleges are usually in a campus that's rather set aside from the arts and science campus."

Cech uses an analogy from physical chemistry to explain the challenge. "There's a term in physical chemistry called 'productive collisions.' In order for two molecules to react, they have to react with a velocity and an orientation suitable for going along the reaction coordinate. We think about people the same way. It helps both launch and sustain interdisciplinary research to have people making 'productive collisions.' If they're rattling around in separate boxes, they don't collide."

Barriers: Funding Organizations and Peer Review

Following World War II, the U.S. federal government assumed the primary role of funding basic scientific research, with the establishment in 1946 of the Research Grants Office at the National Institutes of Health (NIH) and the establishment in 1950 of the National Science Foundation (NSF). According to the annual research and development analysis of the American Association for the Advancement of Science, federal funding for basic and applied research totaled $56.5 billion in 2005.

While the federal funding system of competitive, peer-reviewed grants has been highly successful in advancing American science during the past six decades, the structure and mechanics of the system present some barriers for interdisciplinary research.

The peer review system that lies at the heart of the federal funding process mirrors the disciplinary structure of science. Grant proposals in solid-state physics are reviewed by solid-state physicists, and grant proposals in cell biology are reviewed by cell biologists.

Hildebrand says, "the guild mentality is very dramatic at the funding agencies, but lots of interesting problems that we have to solve in this world don't fall neatly into biology or physics." Hildebrand cites the hypothetical example of an interdisciplinary proposal that includes elements of three different disciplines. "The proposal comes in and it's sent out to three different panels—three different 'guild groups.' Each panel says, 'It looks interesting. It looks good to us. But it's not what we do.'"

Ellis acknowledges this challenge. "Nucleation and growth of any research area benefits from the development of a strong, identifiable community. This process can be particularly challenging for interdisciplinary fields during their formative stages, because researchers from different disciplinary cultures need to learn to communicate. And funding agencies need to ensure that there is appropriate expertise to evaluate proposal ideas."

> …there is a difference between being convinced and being stubborn. I'm not certain what the difference is, but I do know that if you butt your head against a stone wall long enough, at some point you realize the wall is stone and that your head is flesh and blood. — MAYA ANGELOU

In the current (and foreseeable future) climate of tight federal funding for scientific research, the peer review process itself is coming under increasing challenge. Petsko says, "The peer-review system is broken. When you can only fund grants at the tenth percentile, the peer-review process is likely to be conservative. Study sections try to find reasons not to fund a proposal. It's easier to nitpick interdisciplinary proposals to death. When they don't know how to evaluate something, they protect their own turf. Interdisciplinary research crosses boundaries, pushes frontiers. Of course there will be questions!"

The barriers between discipline-based NSF panels or NIH study sections are further magnified at the interface of the physical sciences and life sciences. Strong cultural differences between NSF and NIH can present major obstacles.

Keller says, "There's a tension between NSF and NIH. The side of NSF that supports the physical sciences is chary about supporting work in the biological area. Their argument is that NIH has so much more money that we ought to turn to NIH and let them support that. But when you turn to NIH, you find that their traditions are based on disease hypotheses. If you come in with a phenomenological research proposal, such as wanting to study the interaction between cells and surfaces, they ask you 'what is your disease hypothesis?' They're not structured to see problems defined the way they are defined in the physical sciences."

An additional cultural difference between NSF and NIH is the content and format of the proposal itself. Hopfield, who works at the interface of physics and biology, says, "They have very different cultures for how proposals are written. At NIH, you'd better have half of the research already done in order to provide preliminary data and write a convincing methods section. In biology, you really have to convince someone that you can do the research, no matter how imaginative it is. In physics, however, a physicist thinks, 'If you already know you can do something, why do it?' These differences are hard to swallow and make funding at the interfaces difficult. The most successful interfacial funding I've seen is when one scientist steps forward and tells his collaborator, 'I know how to write an NIH proposal. So you provide the background and all the information, and I will take care of writing the proposal.' That often solves the cultural problem."

Scientists interviewed for this article mentioned a number of other administrative and structural barriers at funding agencies. Until very recently, for example, NIH has only allowed one principal investigator on a grant. Well-intentioned programs can suffer from guidelines that are too narrowly written. Funding agencies have historically given grants more for technology advancement than for solution and application feasibility, approaches which are usually more interdisciplinary. Program officers often lack the flexibility and independence that would allow them to fund proposals that are slipping through the cracks for the wrong reasons.

However, a caution is noted by Edward Penhoet, a biochemist and president of the Gordon and Betty Moore Foundation, who says, "There is a lot of movement at NIH to drive things in the direction of interdisciplinary research. While this may be a good thing, we still need to make sure there's room in the university for the totally independent thinker who wants to work by himself. My own view is that interdisciplinary research should not become the Holy Grail of science, because to force people to do interdisciplinary research when they don't really want to do it is not productive either."

Options: Alternative Institutional Structures

Most universities and colleges use traditional departmental structures for organizing curricula, hiring faculty, administering budgets and salaries, assigning teaching responsibilities, and allocating laboratory and office space. However, an increasing number of institutions are adding alternative structures, with a primary goal of facilitating interdisciplinary research. And some institutions already have a long history of structures that encourage interdisciplinary research.

One such institution is the University of Arizona. Joaquin Ruiz says, "The U of A is a place where interdisciplinary research is incredibly common and has been common for a long, long time. Some of the strongest departments in the university are interdisciplinary—planetary science, geosciences, astronomy, optical sciences and tree-ring research. Those fields are not what you would consider ‘fundamental’ sciences. They came into existence because somebody in the past was hired, and they created an institute.”

In 1979, a grassroots group of scientists (primarily physicists) established the Arizona Research Laboratories (ARL) to support and promote interdisciplinary collaborations at the university. ARL currently comprises eleven divisions, including units devoted to fullerenes, insect science, surface science, neurobiology and microcirculation.

Another successful example of an interdisciplinary institute is the Center for Theoretical Biological Physics, an NSF-sponsored center founded at the University of California, San Diego (UCSD), as a partnership between UCSD, the Scripps Research Institute, the Salk Institute for Biological Studies, and the San Diego Supercomputer Center.

José Onuchic, a co-director of the center, says, “The center is based on two concepts. First, as biology becomes a more quantitative science, theory becomes important. We’re using the current knowledge of physics to understand biological problems, but we’re also using the challenge of biological problems to learn new physics.”

Onuchic continues, “We try to break conventional borders as much as we can. The funding we get for the center sponsors only people who are working on unconventional problems. Research areas that are more established, like my group’s work on protein folding, don’t get funded through the center. The people working with me through the center are working in new fields without established funding—like genetic networks.”

Onuchic says, “The second concept behind the center is the importance of creating a network of people. We have about twelve senior people, fifty graduate students, and fifty post-docs, and we foster a lot of collaboration among them. You have a lot of people interested in theory applied to biology, all together in the same physical space. The senior people talk a lot to each other, and we create a lot of interaction among the young people. The students and post-docs don’t work only on their own problem, but they also know a lot about what other people are doing. The grad students and post-docs gradually realize that they are not working for a single person. They realize they can exploit lots of people. That’s the environment that makes the place… boom!”

The University of Arizona and the University of California, San Diego, are just two among a number of institutions with long records of encouraging interdisciplinary research. One of the premier examples is Rockefeller University.

Instead of being organized into traditional academic departments, Rockefeller University is centered around seventy-five cutting-edge laboratories working in a broad range of fields—from cell and developmental biology to neuroscience, from biophysics to biochemistry. According to Hildebrand, who spent time at Rockefeller as a graduate student and faculty member, “The university faculty is organized around individuals. A senior professor defines the mix of things that is done in the ‘department’ that is the entourage around that person. So it’s a kaleidoscope. Every time someone leaves and someone else comes, you rotate the kaleidoscope and you have a different pattern. This is getting back to the way I imagine it was organized in medieval Europe, where things were defined by the Master around whom students gathered.”

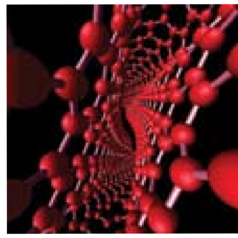
Hildebrand says, “Rockefeller provides an example of how you could organize things differently. Admittedly, they don’t face the same challenges that a typical college or university does, because they don’t have to offer curricula for undergraduates. They have a very broadly interdisciplinary Ph.D. program where incoming students don’t actually declare what field they are going to work in. Students can move around as their interests evolve. When I was there, it was amazing, you saw people coming in doing physics and winding up doing phage microbiology, and vice versa.”

Another institution that’s thrived for decades without any academic departments is the Salk Institute for Biological Studies in San Diego, established in the 1960s by Jonas Salk, developer of the polio vaccine. Charles Stevens, professor of molecular neurobiology at Salk, says, “We’re a small institution, with about fifty laboratories that cover much of modern biology. We have no departmental structure; every laboratory is independent. We have no department chairmen. Nobody has more space than anybody else, so you can’t build an empire. You have your laboratory and that’s it, so there’s nothing to fight over. There are no departmental barriers, no spatial barriers. Everyone is high-quality, hard-working, and passionate about their science. It makes it very easy to do collaborative work.”

In the last decade, many universities and colleges have begun experimenting with innovative institutional structures to foster interdisciplinary teaching and research. Among the promising innovations mentioned by scientists interviewed for this article are the following:

- Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign
- Bio-X program, Stanford University
- BIO5 program, University of Arizona
- Center for BioDynamics, Boston University
- Center for Quantitative Life Sciences, Harvey Mudd College
- Institute for Systems Biology, a Seattle-based research institute that is building strong partnerships with Fred Hutchinson Cancer Research Center and the University of Washington
- Lewis-Sigler Institute for Integrative Genomics, Princeton University

Perhaps the biggest, grandest experiment of them all is Janelia Farm Research Campus, an advanced research center established by the Howard Hughes Medical Institute (HHMI) at a development cost of $500 million. When completed mid-2006, Janelia Farm, located in Loudoun County, Virginia, will serve as an intellectual hub for several hundred scientists from diverse disciplines. These scientists will work in multidisciplinary teams to solve challenging biological problems that are difficult to address in existing research settings. The various elements of the Janelia Farm project—including the reward structure for scientists, the physical space, the scientific content areas, and the funding structure—have all been designed to minimize potential barriers to collaborative, interdisciplinary research.



Cech says, “You have to realize that Janelia Farm is, in a sense, an easy solution. This isn’t a general solution. This is like cheating, because you have the opportunity to do something *de novo*, with knowing all of these shortcomings. So you solve the problems—or we hope we will solve them. It doesn’t mean other people are doing things wrong, but we have an opportunity to do things in a different way and to prevent these problems from the beginning.”

Petsko emphasizes that interdisciplinary institutes are experiments. “Anybody who tells you they know how to do it right is fooling themselves. I don’t know how to do it best, but I do know that we’ve got to start trying. We’ve got to do a lot more, because we don’t know what models work. We need to find out. If there’s one way to do it right, you could fund six centers and be done—but it’s not like that.”

These high-profile experiments demonstrate what can be done to break down barriers when an institution has the financial resources and vision to try something bold and radical. Often, however, it’s not feasible to create a new institute or a new administrative structure. Fortunately, change and progress don't always require a big name and big bucks.

Facilitating Interdisciplinary Research lists dozens of recommendations for institutions interested in making changes. Here are five of those recommendations that could be applied without establishing a new center:

- Provide mechanisms to build a community of interdisciplinary scholars across the institution similar to the community that is in a department.
- Selectively apply pooled faculty lines and funds available for startup costs for new faculty toward recruitment of faculty with interdisciplinary interests and credentials.
- Experiment with administrative structures that lower administrative and funding walls between departments and other kinds of academic units.
- Credit a percentage of all projects' indirect costs to support the infrastructure of research activities that cross departmental and school boundaries.
- Create a campuswide inventory of equipment to enhance sharing and underwrite centralized equipment and instrument facilities for use by interdisciplinary research projects and by multiple disciplines.

As illustrated by these examples, there are many options for scientists and administrators to consider.

Keller sums up the issue of institutional change this way, "I don't think there are magic bullets. I think there are approaches that let you take advantage of possibilities. I do think you need to provide support mechanisms for interdisciplinary centers. But you also need to change the structure of universities so that the disciplinary departments have some sense of ownership in that. You've got to give departments a stake in the success."

Keller advises, "The eventual solutions will get very institutionally dependent. MIT has one approach. Here at Minnesota we'd have another approach. Stanford would have a third approach. The idea is to figure out ways of encouraging and supporting people to work in these areas, and an important part of that is getting departmental buy-in. Each institution is going to have to look at its own situation—its size, its ratio of undergraduate to graduate students, whether or not it has a medical school. Each institution is going to have to do it differently."

Options: Tenure, Promotion and Career Transitions

Just like any organism that passes through key developmental stages, there are important and precarious transition points in the career of an interdisciplinary scientist. Programs that ease those transitions will serve the long-term future of interdisciplinary research.

Kopell believes that the transition from post-doc to assistant professor is perhaps the most challenging transition. "People come out of interdisciplinary programs, and they ask, 'Do I belong in a math department or a biology department? Who am I? What am I going to be when I grow up?' This is really tough. One of the emotionally hardest parts of my job is hiring season, when I wonder who's going to fall through the cracks. It has to do with the structure of departments, because departments think of themselves as 'We are *x*. This is our identity. Does *y* fit in our department?'"

Kopell continues, "My feeling is that the tenure process is less of a problem once people have been hired. They won't be hired in a tenure-track position unless there are enough people around who value them for their generalized skills. If they go about doing what they say they're going to do, they will get tenure. The problem is getting them hired in the first place."

One program addressing this particular transition point is the Career Awards at the Scientific Interface program. Funded by the Burroughs Wellcome Fund since 2002, these grants "are intended to foster the early career development of researchers with backgrounds in the physical/computational sciences whose work addresses biological questions and who are dedicated to pursuing a career in academic research." The grants provide $500,000 over five years, supporting up to two years of advanced post-doctoral training and the first three years of a faculty appointment.

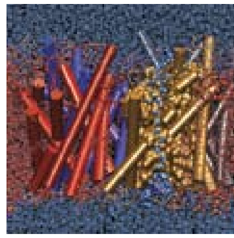
Kopell notes that administrators greatly appreciate a young faculty member whose early salary is being paid by someone else. "It helps them get their foot in the door. And if they do well, it enables them to keep going."

> What a troublesome thing a wall is! I thought it was to defend me, and not I it! Of course, if they had no wall, they would not need to have any sentinels.
>
> — HENRY DAVID THOREAU

Once a young scientist is hired to a tenure-track position, the major barrier of tenure criteria becomes a key concern, especially the issue of collaboration.

Petsko says, "I've seen it happen too many times—that somebody is criticized for being highly collaborative and interactive. And that's just not right. I think we need to change our view of what constitutes an original and independent contribution. It does not need to be stuff you only do in your own lab. I think we ought to reward people who build bridges to other groups, who are community minded, who are inclusive. If we don't make a conscious decision to change the way we think about that, we won't."

In Petsko's own career, he's worked very closely for twenty-five years with another faculty member, Dagmar Ringe, sharing projects and research groups. Petsko says, "Most of the work we've done, it's completely impossible to tell who's been largely responsible for this or that. And why should you care? I guarantee you that I wouldn't be as good a scientist as I am if she weren't working with me. So why should the university not be thrilled by that? They're getting better scientists as a result of this collaborative effort."



Petsko cites several other examples of highly successful and highly collaborative research teams, including Michael Brown and Joseph Goldstein (1985 Nobel Laureates for their discoveries concerning the regulation of cholesterol metabolism) and Don Wiley and Stephen Harrison (work done at Harvard to help establish the new field of structural biology). Examples from the history of science also abound, with the most notable example probably being Watson and Crick.

Petsko's suggestion on how to tease out the individual contributions within a collaborative relationship? "I don't know that I would. I don't know that it's an appropriate judgment to make. Look… if the person is in your department, you know whether they're any good or not. If you have to rely on outside letters, what the hell are you doing voting? If we're talking about multiple people in a department, why not consider them as a team?"

Other institutions, particularly in industry, have proven the value of recognizing and rewarding teamwork. Hopfield's experience with Bell Laboratories, where scientists working on collaborative projects each received full credit, provides a good example. "Management carefully rewarded projects that were successes and involved cooperation. They did this with salary increases, minor perks, and pats on the back. They did this because they wanted successful research results. They were always asking, 'How can we best motivate our researchers to do the best science they can?'"

Penhoet, one of the founders of Chiron Corporation and for seventeen years its president and chief executive officer, says, "In companies, at the end of the day, projects only work if you have a whole bunch of people working in teams. I think one of the biggest differences between doing science in a university and doing science in the commercial world is teamwork. Industry is quite far ahead of universities. There it's expected that you work in teams. The work requires it. As you develop health care products, you have to bring in lots of technology to make things work. You have to do a lot of different kinds of testing. In young companies, one of the strong financial motivators is stock options. If a company is successful, people who work there will be financially rewarded. So they get a reward for working in teams."

At Janelia Farm, the potential conflict between collaboration and promotion is being handled right up front. Cech says, "We can prevent that conflict at Janelia Farm by announcing at the beginning, 'If someone is a middle author and contributes their talent, energy and innovation to a project, they'll be held up as an example.' Not only will they be recognized, but, in fact, that's the concept we're working toward."

In addition to the specific issue of rewarding and recognizing collaborative research, other recommendations for addressing the tenure criteria issue include the following, taken from *Facilitating Interdisciplinary Research:*

- Provide more flexibility in promotion and tenure procedures, recognizing that the contributions of a person in interdisciplinary research may need to be evaluated differently from those of a person in a single-discipline project.
- Establish interdisciplinary review committees to evaluate faculty who are conducting interdisciplinary research.
- Extend the venue for tenure review of interdisciplinary scholars beyond the department.
- Increase recognition of co-principal investigators' research activities during promotion and tenure decisions.
- Develop mechanisms to evaluate the contribution of each member of an interdisciplinary research team.
- Experiment with alternatives to departmental tenure through new modes of employment, retention and promotion.

The opportunity to encourage and reward interdisciplinary research does not stop with the tenure decision. In fact, a number of scientists suggest that programs that support senior scientists to move across disciplines are equally important.

One example of such a program is found in Sweden, where the Senior Individual Grants competition was established in 2003. The program targets internationally recognized senior scientists, working in Sweden, "who want to renew their research and explore new ideas, preferably of a cross-disciplinary, integrative nature." Stage 1 provides financial support for a one-year sabbatical. Stage 2, a competition open only to those selected for Stage 1, provides grant support for research activities over three years. The purpose of the second grant is to make it possible to realize a research project in Sweden, based on the inspiration and experience obtained during Stage 1.

Petsko, who serves as an outside reviewer for the Swedish Foundation for Strategic Research, which sponsors the competition, is a strong supporter of the program and thinks the United States could benefit from a similar program targeted at mid-career and senior scientists. "Once you have established yourself as a young scientist, the conservative funding system, which tends to prefer giving money to things that seem likely to work rather than to things that are innovative and therefore risky, rewards those with a track record so long as they continue to do

the things they have a track record in. Try working in a new area and you will often be discounted as overly ambitious (read, 'naïve') or unfocused (read, 'straying too far from your own turf'). Anyone with a new idea faces these problems, of course, but they're particularly acute for the middle-aged scientist." ("Sweden Has the Right Idea," *Genome Biology,* 2006, 7:103)

In the United States, beginning in 2007, a select group of scientists, including many falling into this 'mid-career' age range, will find a welcoming environment at Janelia Farm. Through its Visiting Scientist program, Janelia Farm will typically be hosting about 100 visiting scientists on site. These visiting scientists will include current HHMI investigators, short-term visitors collaborating with resident staff or using atypical research facilities, and project teams.

Cech expects that the Visiting Scientist program will have ripple effects throughout the scientific community, spreading the word about the value of collaborative, interdisciplinary research. "We'll have a lot of visitors going back to their home campus saying, 'You won't believe what I just saw. We've got to try some of that here.'"

Options: Education and Training

Innovations in education and training can catalyze interdisciplinary research—both now and in the future. And the benefits accrue to students, faculty and institutions.

At the undergraduate level, several recent national initiatives are pointing the way to curricula that will give today's students the education required to be tomorrow's scientists.

In *BIO2010: Transforming Undergraduate Education for Future Research Biologists (2003),* the National Research Council's Committee on Undergraduate Biology Education to Prepare Research Scientists for the Twenty-first Century addresses issues related to undergraduate education of future biomedical researchers. The committee made eight major recommendations including the following:

> "Concepts, examples, and techniques from mathematics, and the physical and information sciences should be included in biology courses, and biological concepts and examples should be included in other science courses. Faculty in biology, mathematics, and physical sciences must work collaboratively to find ways of integrating mathematics and physical sciences into life science courses as well as providing avenues for incorporating life science examples that reflect the emerging nature of the discipline into courses taught in mathematics and physical sciences."

The chemistry community is also embracing the need to update the undergraduate curriculum. In recent years, the American Chemical Society, with funding from NSF, has developed several innovative textbooks that are changing the way chemistry is taught for both science majors and non-science majors. *Chemistry: A General Chemistry Project of the American Chemical Society* (published by W.H. Freeman and Co., 2004) covers traditional general chemistry topics in a non-traditional order. Biochemistry, organic chemistry and environmental chemistry are introduced early and integrated throughout the text, allowing students to see the relevance of what they're learning to the world around them. Chemical principles are introduced in the

context of biologically important molecules, beginning with water.

With curricular innovations such as these at the undergraduate level, more students will be attracted to the sciences. Interdisciplinary courses and research projects at the undergraduate level excite and motivate today's students. When colleges and universities offer courses in interdisciplinary topics, such as forensic science, environmental science or biomedical engineering, they find rising enrollments. According to Hildebrand, these types of courses can "serve as a pump rather than a filter," bringing new students into the sciences, rather than weeding them out.

Kopell says, "You can get an undergrad excited about interdisciplinary fields, and that's a very good thing. But you can't get them fluent, because there's so much to learn. You can provide opportunities to see what is out there, but that's a very different problem from the training. The key to interdisciplinary research is training, training, training."

The real training to become an interdisciplinary scientist, then, begins in earnest at the graduate level. A number of institutions are experimenting with interdisciplinary approaches to graduate training.

In San Diego, Onuchic and colleagues are using a "dual mentor" approach. In a training program called "La Jolla Interfaces in Science," originally supported by the Burroughs Wellcome Fund, pre-doctoral and post-doctoral students propose research projects that require the participation of two mentors—one from the quantitative sciences and one from the biological sciences. With students participating in two group meetings, this approach has proven more effective than coursework at engaging students in the culture, language, technology and literature of two scientific disciplines.

Onuchic maintains that the dual mentor approach is "the best way to train students. Students learn they can move into a different and difficult field. They learn, 'I can do it.' After that, they're not scared to do something different." Onuchic cautions that post-docs with dual mentors should plan on a three-year post-doc appointment instead of a two-year appointment, because "it takes more time to learn two languages."

Onuchic observes, "Students from this program have been successful finding jobs. Eighty percent are now professors. They are a new brand of professor, because they can talk to both departments. They may be 'foreigners' and 'speak with an accent' but at least they can speak the language."

Kopell's experience at Boston University's Center for BioDynamics has been similar. She says, "We use the 'total immersion technique' around here. When students show up, they sometimes know no neurobiology. I point out two or three large textbooks, and I say, 'Start reading. Start asking questions of everyone in sight.' Part of the ethos of the place is that whatever you know, you teach everyone else. What you don't know, you can ask anybody else. It's a very kibbutz-like ethos: 'from each what he can afford, and to each whatever his needs are.' And it works. With immersion, you learn it much more quickly than you do from classes."

The National Science Foundation has encouraged the development of innovative graduate programs through its IGERT program—the Integrative Graduate Education and Research Traineeship program. Launched by NSF in 1997, it now supports students at approximately 125 award sites. According to NSF, the program "is intended to catalyze a cultural change in graduate education, for students, faculty, and institutions, by establishing innovative new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries."

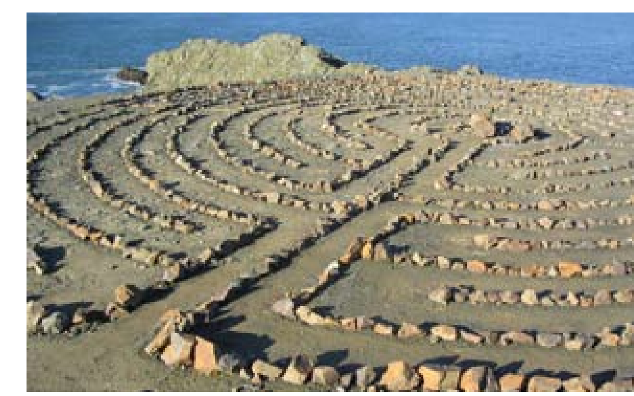
The University of Arizona has developed a number of IGERT programs in areas such as Interface of Biology, Mathematics and Physics; Archaeological Sciences; and Genomics. Ruiz says, "These IGERT programs, if they're good, can actually give you the intuition you need to work effectively on the boundaries. I think they're wonderful. They've been a boon. When you create structures where graduate students can go backwards and forwards, the students become the pollinating agents between senior scientists who are really busy."

Hopfield agrees that interdisciplinary training programs can bring important benefits to faculty members and the institution. While a faculty member at Cal Tech, he observed that if "an education program is centered in the interstice between disciplines, that's what's going to attract the bright people. And bright students are a marvelous form of glue. It has the effect of bringing together people from different disciplines to plan the education—to say what additional courses are needed, to ask what kind of examinations are needed, to see how to nurture those students. That committee work actually helps the faculty interact in an interesting fashion. It's a marvelous side-effect of an education program."

Options: Innovative Spaces to Foster Communication

Collaborative, interdisciplinary research doesn't always require new institutes, new curricula, new degree programs and new tenure criteria. Sometimes, according to Richmond, "it just comes down to people going across the hall, talking to someone, and getting it going."

Of course, it helps if the scientist across the hall happens to be interested in similar topics, with a set of skills and technologies rooted in a different but complementary discipline. With the traditional, discipline-based arrangement of office and lab space at most institutions, the likelihood of finding such a collaborator across the hall is very low.



At the University of Oregon, however, where Richmond is a professor of chemistry, disciplines have been mixed for more than twenty years. "Our scientific research enterprise was largely created here in the 1950s. Molecular biology was a major player at that time in its growth, leading the charge to create a model that supported interdisciplinary research. Because it was shown to be such an effective model, the buildings were then constructed around that theme. I'm in a physics building as a chemist, and I'm down the hall from biologists. It's a really remarkable building."

Richmond continues, "We've gotten so used to it that we don't even think about it anymore. Great science comes out of it, but you don't distinguish what's across departments versus what's in your department. It works and it's largely seamless. The biggest benefit is to the students, because the chemistry graduate students hang out with the physics and biology graduate students. They're not so pigeonholed into one department. If I go to a party with graduate students—even when it's a relatively small gathering—there are chemists, biologists, and physicists there. They don't think anything of it. I just wish the business school and the rest of the university were attached to us, too."

It isn't always necessary to construct a new building in order to bring together scientists from different disciplines and cultures. Ruiz offers an example at the University of Arizona involving the Department of Molecular and Cellular Biology (in the College of Science) and the Cancer Center (in the College of Medicine). "The director of the Cancer Center and I decided that I would hire some faculty in molecular and cellular biology but that they would actually have their laboratories in the Cancer Center. So, basically, we stuck these folks in another building with all these doctors. It's been a very interesting experiment. We hired some folks that hated it. We had to move them back to the College of Science, because they felt that they didn't have the right people to talk to. But we've also hired some people that just love it. They're doing all kinds of experiments that are translational in nature. The Cancer Center loves it, and they've really fit in there."

Sometimes the innovation is as simple as seating arrangements, common space and free coffee. At the Center for Theoretical Biological Physics in San Diego, says Onuchic, "graduate students and post-docs don't sit by groups. They're all mixed up in a common area. In every big area where students sit, there's a discussion area where they can get together. We always keep the espresso machine on. Networking is a very important thing. Make sure they share a physical space so people collide with each other—as often as possible. That's the idea of the center. You have to force synergy."

When the financial resources are available, a number of institutions are putting up new buildings that will house scientists from different disciplines. Stanford's Bio-X program uses the new James H. Clark building as its home. Within the Clark Center are sixty-five bright yellow three-foot benches—known as "Hotel Space"—that are available to researchers for temporary occupancy. The benches provide an opportunity for researchers to work in close proximity during the early stages of projects.

At the University of California, Berkeley, a new multi-disciplinary building is scheduled for completion later in 2006. As part of the Berkeley Health Sciences Initiative, the Stanley Biosciences and Bioengineering Facility will house more than forty researchers from bioengineering, molecular and cell biology, physics, chemistry and computer science. According to Penhoet, who was a leader in launching the Health Sciences Initiative when he was dean of Public Health from 1998 to 2002, "It's novel. Historically at Berkeley, each building belonged to a department." One of the design elements included to foster collaboration will be computational suites. Interwoven among traditional laboratories, these suites, by their co-location, will enhance a synergistic relationship between experimental and theoretical approaches to research problems.

At the Lewis-Sigler Institute for Integrative Genomics at Princeton, a number of different disciplines share one building, the Carl Icahn Laboratory. Hopfield says, "Space really does matter. The atrium of the building, with a little café in it [called the "Genomics Café"], has become a crossroads. People come here for lunch from other buildings or stop here to pick up their morning coffee. It works in a way which I wouldn't have been able to envision. I'm really quite astonished at what it contributes to the life of the building. It's built in such a way that everybody sees that space quite constantly. So there's a real feeling of interaction with all other people in the building."

At Janelia Farm, the goal of helping scientists interact through "productive collisions" lies at the heart of the campus design. According to the Janelia Farm website, "The planning for both the scientific program and the campus facilities was intertwined, with each part overlapping and influencing the other. The architectural designs of the buildings and the laboratories are aimed at achieving Janelia Farm's central objectives—collaboration and flexibility." Among the features that support these goals are the following:

- Clustering of offices and the inclusion of larger shared laboratory spaces to encourage collaboration among small groups
- Location of office clusters to reflect the programmatic need for a very close tie between the laboratory spaces and the office spaces
- Significant amount of conference space, including meeting spaces, student study places, social spaces and conference housing
- On-site housing and related amenities to support the visiting scientist program

Options: Funding and Funding Organizations

Funding organizations, both federal agencies and private foundations, are keenly aware of the need for programs that support and encourage interdisciplinary research. In recent years, a number of programs have been established towards this end.

At the National Institutes of Health, the guiding vision for future directions is the NIH Roadmap, a planning approach introduced by NIH director Elias Zerhouni in 2002. One of the priorities emerging from the Roadmap process is "Research Teams of the Future: Interdisciplinary Research." The NIH Roadmap website includes this description of the NIH response to the challenge of interdisciplinary research:

> Health research traditionally has been organized much like a series of cottage industries, lumping researchers into broad areas of scientific interest and then grouping them into distinct, departmentally based specialties. But as science has advanced over the past decade and the molecular secrets of life have become more accessible, two fundamental themes are apparent: the study of human biology and behavior is a wonderfully dynamic process, and the traditional divisions within health research may in some instances impede the pace of scientific discovery.
>
> To lower these artificial organizational barriers and advance science, this set of NIH Roadmap initiatives will establish a series of awards that make it easier for scientists to conduct interdisciplinary research. These new awards include funding for: training of scientists in interdisciplinary strategies; creation of specialized centers to help scientists forge new and more advanced disciplines from existing ones; supplements to existing awards which encourage interdisciplinary depth for an ongoing project; and planning of forward-looking conferences to catalyze collaboration among the life and physical sciences, important areas of research that historically have had limited interaction.

In addition to these funding initiatives, NIH is introducing some important changes in the grantmaking process. In particular, rather than recognizing only a single Principal Investigator (PI) for every award, NIH is now moving toward recognition of multiple PIs for any award. To address the barrier presented by the traditional peer review process (i.e., the "guild mentality" or "clubbiness" mentioned by some critics), NIH is considering alternate review strategies for interdisciplinary research.

At the National Science Foundation, interdisciplinary research has been an important priority for a number of years. Over the past two decades, there has been a steady growth in the number of grants awarded to multiple PIs. (The National Academy of Public Administration has concluded that the best current measure of interdisciplinary research at NSF is multi-investigator grants.) In 1982, for example, multi-investigator proposals received about 26 percent of total grant funding. By 2001, that number had risen to 50 percent. NSF's Science and Technology Centers (STCs) and Engineering Research Centers (ERCs) have served as models for interdisciplinary centers at universities. Included in the NSF initiatives mentioned by scientists interviewed for this article are the IGERT program and the Frontiers in Integrative Biological Research (FIBR) program.

Other federal agencies that support interdisciplinary research include the Department of Energy (with its GTL program), the Department of Defense (with its DARPA program) and NASA (with its Astrobiology Institute).

In recent years, federal agencies have sought to better coordinate their funding programs and to establish programs that span the agencies. One such example at the interface of the physical and life sciences is Collaborative Research in Computational Neurosciences (CRCNS), an interagency program supporting interdisciplinary research on brain function. For the program, projects are supported through the combined efforts of five participating NSF Directorates and nine NIH Institutes. Initial proposals are submitted to NSF for review. Following the review process, program officers from participating NSF/NIH units meet and determine which proposals will be funded by which directorate or institute.

While federal funding agencies provide the lion's share of funding for scientific research in the United States, private science foundations have historically played an instrumental role in establishing new fields of science. Research Corporation, through its early support for Grote Reber and other astronomers, helped launch the field of radio astronomy. The Whitaker Foundation has played an enormous role in establishing the interdisciplinary field of biomedical engineering. In his book, *A History of Molecular Biology,* author Michel Morange devotes an entire chapter to "The Influence of the Rockefeller Foundation."

In recent years, private foundations have continued to stake out emerging fields where they can make a difference. Because private foundations, compared to federal agencies, are often able to move more quickly to address needs and take advantage of opportunities, many of the foundation-supported fields have been highly interdisciplinary.

The Sloan Foundation, in 1994, established five research centers in theoretical neurobiology, including one at the Salk Institute. According to Stevens, "the idea was to bring people with training in quantitative sciences into biology. Physicists, for example, could come and immerse themselves in biology. Then they could be the bridging person in a collaboration between quantitative scientists and biologists." One such individual cited by Stevens is Dmitri Chklovskii, trained as a condensed matter theorist, who became immersed in biology while working with Stevens. Now, after working at Cold Spring Harbor, Chklovskii will be heading up one of the laboratories at Janelia Farm. Stevens says, "He can communicate with both the quantitative people and the biologists. The key is to have someone that bridges the two areas, because otherwise the two cultures are too different."

The F.W. Olin Foundation gave $460 million to found a new college of engineering, Olin College, in Needham, Massachusetts. The college, which opened its doors in 2002, has no departments, and many of its classes employ an interdisciplinary approach. "In most engineering schools, it's learn, then do," says Olin's president, Richard Miller. "We turn that around: Do, then learn. It's learning to swim in the deep end." The Olin curriculum emphasizes an interdisciplinary approach, teamwork, hands-on design, business, creativity and communication.

The Gordon and Betty Moore Foundation currently supports a major initiative in marine microbiology. Penhoet says, "One of our four filters for grantmaking is 'can we make a difference?' We saw a point in time where genomics was about to revolutionize the field, where the field as a whole was underfunded, and where if we came in strength we could make a real impact on the future of the field. Sequencing has broken the whole field open. We think that understanding the microbes of the ocean is critical to understanding the food webs in the ocean and the productivity of the ocean."

As illustrated with examples earlier in this article, the Arnold and Mabel Beckman Foundation, the Burroughs Wellcome Fund, the Howard Hughes Medical Institute, the W.M. Keck Foundation and the John D. and Catherine T. MacArthur Foundation are making major contributions to the advancement of interdisciplinary research.

Conclusion: Stepping into the Gaps

Robert Frost believed that the power and mystery of nature cannot be constrained by manmade walls. This suggests that individuals can, and should, pass through the gaps in walls wherever they appear.

This article has pointed out some of the manmade, discipline-based walls and barriers that have arisen in science. Yes, walls—and scientific disciplines—can serve useful and important purposes.

Yet it is becoming increasingly clear that many of today's scientific opportunities and challenges are calling on individuals and institutions to lower barriers, put in gateways, and dismantle walls between disciplines, departments and laboratories—and to step into the gap.

Five years ago, Rita Colwell, director of the National Science Foundation, delivered the annual James A. Shannon Lecture at the National Institutes of Health. In her speech, titled "Crossing Borders: Science, the Public, and New Policies," she quoted Frost's poem and said, "In its broadest and deepest purport, scientific enlightenment 'doesn't love a wall.' In this new age of exploration, borders of all kinds are shifting and dissolving, and walls are coming down."

She continued, "We've profited mightily from past specialization in the various disciplines, and we'll continue to reap this harvest in the future. But the synthesis that results from viewing phenomena across multiple scales and from the perspective of many disciplines gives us a powerful new capability. The robustness of our science increases as we expand the territory covered by a common groundwork of explanation."

The call for interdisciplinary research is issued by nature, through complex phenomena seeking to be understood, and by society, through global problems seeking to be solved.

As illustrated by the options included in this article, the response to that call will come from each of us in our own way—from students, junior scientists and senior scientists; from departments, colleges and universities; from centers, institutes and programs; and from funding agencies, both public and private.

As Research Corporation responds to the challenge of interdisciplinary research, we encourage you to consider how you, your colleagues, your students and your institutions will respond as well.

Before I built a wall I'd ask to know
What I was walling in or walling out,
And to whom I was like to give offence.
Something there is that doesn't love a wall,
That wants it down.

— ROBERT FROST, "MENDING WALL"

Scientists interviewed for this article include:

Thomas R. Cech is President of the Howard Hughes Medical Institute and Distinguished Professor of Chemistry and Biochemistry at the University of Colorado at Boulder.

Arthur B. Ellis is Director, Division of Chemistry, National Science Foundation, and Meloche-Bascom Professor of Chemistry at the University of Wisconsin, Madison.

John G. Hildebrand is Regents Professor of Neurobiology, Biochemistry and Molecular Biophysics, Entomology, and Molecular and Cellular Biology and Director, Arizona Research Laboratories Division of Neurobiology at the University of Arizona.

John Hopfield is Professor of Molecular Biology at Princeton University.

Kenneth H. Keller is the Charles M. Denny Jr. Professor of Science, Technology and Public Policy and Director of the Center for Science, Technology and Public Policy at the Humphrey Institute of Public Affairs at the University of Minnesota.

Nancy J. Kopell is Professor of Mathematics and Co-Director of the Center for BioDynamics at Boston University.

Randall S. Murch is Associate Director for Research Program Development in the Office of the Vice President for Research; Adjunct Professor in the Department of Plant Pathology, Physiology and Weed Science; and Adjunct Professor at the School of Public and International Affairs at Virginia Polytechnic Institute and State University (National Capital Region Operations in Alexandria, Virginia).

José N. Onuchic is Professor of Physics and Co-Director of the Center for Theoretical Biological Physics at the University of California at San Diego.

Edward E. Penhoet *(not pictured)* is President of the Gordon and Betty Moore Foundation.

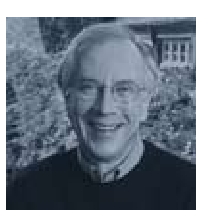
Gregory A. Petsko is the Tauber Professor of Biochemistry and Molecular Pharmacodynamics and Director of the Rosenstiel Basic Medical Sciences Research Center at Brandeis University.

Geraldine L. Richmond is the Richard M. and Patricia H. Noyes Professor of Chemistry at the University of Oregon.

Joaquin Ruiz *(not pictured)* is Dean of the College of Science and Professor of Geosciences at the University of Arizona.

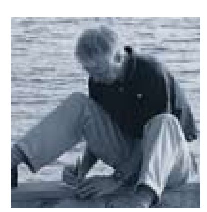
James W. Serum is the President of SciTek Ventures.

Charles F. Stevens is Professor and Vincent J. Coates Chair in Molecular Neurobiology at the Salk Institute for Biological Studies.


Cech


Ellis


Hildebrand

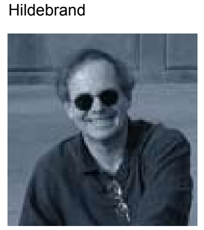

Hopfield


Keller


Kopell


Murch


Onuchic


Petsko


Richmond


Serum


Stevens

Program Review

Funding agencies do not drive the new directions of scientific research. That is the purview of research practitioners in academic, industrial and government research enterprises worldwide. So how does a foundation like Research Corporation–whose mission it is to advance science through support of academic research–facilitate the development of emerging research directions? Foundations need to be vigilant, nimble and take risks. They must recognize research that offers true innovation at the boundaries of new knowledge and has the potential for important breakthroughs early on, and then stimulate such work with support in ways consistent with their mission. It is no secret that science in the twenty-first century is moving toward the interfacial areas at the (arguably artificial) boundaries of chemistry-biology, chemistry-physics and biology-physics. Much of the research done in these areas involves, and indeed requires, a collaborative or team approach. How has Research Corporation responded?

For many years Research Corporation has focused its attention on supporting research in the physical sciences. Indeed, eligibility for our regular programs requires that applicants are members of either chemistry, physics or astronomy departments. While arbitrary, this disciplinary approach to eligibility allows us to keep the number of proposals we have to consider annually to a manageable level consistent with our resources. But this begs the question: Can we effectively facilitate emerging innovative work at the interfaces with this approach? A review of what we have been funding over the past decade indicates that Research Corporation's programs for the college and research university communities have adapted to new research directions. The thrust of proposals received and awards made today has shifted significantly in the past decade. In 1995, we received 246 proposals in the Cottrell College Science program. Of those, 22 percent were biologically based and materials science and nanotechnology made up 10 percent. Of the 288 proposals received in 2005, more than 40 percent were biologically based and included a wide variety of topics in biochemistry-molecular biology, bioorganic, bioanalytical chemistry, and biophysics. Materials science and nanotechnology applications have also approximately doubled to about 20 percent during the past decade. Though the fraction of proposals from the physics community remains at about 30 percent of total proposals, physics research has clearly moved to such areas as photonics, spintronics, nanotechnology and complex systems. These trends are virtually the same in our Cottrell Scholars program as well. This shift in applications and awards made demonstrates that we have responded to the major emerging areas in academic research in the past decade and with significantly greater funding at the interfaces of disciplines. But have we been responsive and flexible enough? If we are going to continue to have an impact with limited resources, we must keep this question in the forefront and remain open to new ways to facilitate the more risky research of faculty who are pushing the boundaries of science.

Raymond Kellman

Vice President

Program Summary

One hundred and twelve awards were made in support of faculty research, research-enhanced teaching and special projects in science in 2005. Funding for the foundation's programs noted below totaled $4,952,974. Seven additional awards were made, totaling $648,000.

COTTRELL COLLEGE SCIENCE AWARDS

Cottrell College Science Awards are the foundation's largest program, supporting faculty in chemistry, physics and astronomy at primarily undergraduate institutions. The program, which encourages student research involvement, funded ninety-three out of 289 faculty applicants. Two cycles of awards are featured each year; in 2005, the foundation granted a total of $3,402,974, averaging $36,591 per award.

COTTRELL SCHOLARS AWARDS

Cottrell Scholars Awards support excellence in both research and teaching in chemistry, physics and astronomy at Ph.D.-granting institutions. Each award totals $100,000, to be used largely at the discretion of the scholar. Out of 136 requests submitted, thirteen Cottrell Scholars awards were made, totaling $1,300,000.

RESEARCH OPPORTUNITY AWARDS

Research Opportunity Awards support midcareer faculty of demonstrated productivity who seek to explore new experimental research at Ph.D.-granting institutions. Out of nine candidates nominated by their department chairs for awards in 2005, five proposals were funded for a total of $250,000.

RESEARCH INNOVATION AWARDS

Research Innovation Awards were instituted in 1997. The Research Innovation Awards program is open to beginning faculty at Ph.D.-granting institutions and encourages innovation by scientists early in their academic careers. During an assessment of the feasibility of this award, this program has been suspended for 2005-2006.

OTHER AWARDS

Also in 2005, one Special Opportunity in Science Award was made, totaling $300,000. In addition, six Discretionary Awards for the year totaled $348,000.

Research Corporation Awards

COTTRELL COLLEGE SCIENCE AWARDS

Adelphi University
Sean J. Bentley, Department of Physics
Nonlinear and quantum optical properties of quantum dots for generation of new sources of quantum states of light—$31,146

Adelphi University
Joshua M. Grossman, Department of Physics
Microscopic magnetic surface traps for individual atoms—$35,644

Amherst College
Anthony C. Bishop, Department of Chemistry
Chemical biology of cancer-associated protein tyrosine phosphatases—$42,184

Appalachian State University
Adrian Daw, Department of Physics
Measurement of atomic and molecular parameters of nitrogen for geophysical, astrophysical and plasma-processing applications—$44,818

Augustana College
Eric Wells, Department of Physics
Exploiting the ground state dissociation of hydrogen molecules as a tool for studying ion-molecule collision processes—$42,289

Ball State University
James S. Poole, Department of Chemistry
A study of the reactivity and kinetics of 3-phenylpropyl radicals—$42,616

Brock University
Travis Dudding, Department of Chemistry
A strategic approach for the development of catalytic enantioselective aza-Stetter reactions—$26,800

Brock University
Costa Metallinos, Department of Chemistry
Approaches to chiral benzimidazolylidenes derived from phenanthrolines—$20,995

Bucknell University
David Rovnyak, Department of Chemistry
Towards new relationships between metal coordination geometry and protein function in unusual zinc-binding cytoplasmic domains—$47,836

California State University, Bakersfield
Alexander Dzyubenko, Department of Physics
Many-body effects in optics of a two-dimensional electron gas in magnetic fields—$30,776

California State University, Long Beach
Xianhui Bu, Department of Chemistry and Biochemistry
Synthesis and characterizaton of cysteine-peptide capped CdS nanoclusters and crystalline superlattices—$35,000

California State University, Long Beach
Stephen P. Mezyk, Department of Chemistry and Biochemistry
Removing carcinogenic nitrosamines from treated drinking water: The chemistry behind advanced oxidation technologies—$35,000

California State University, Long Beach
Katarzyna Slowinska, Department of Chemistry and Biochemistry
Diffusion of molecular probes in a collagen matrix: Understanding hydrophobic interactions in local drug delivery systems—$44,609

California State University, Northridge
Debi Prasad Choudhary, Department of Physics and Astronomy
Chromospheric magnetic field of solar active region— $32,418

California State University, Northridge
Gang Lu, Department of Physics and Astronomy
From electrons to finite-elements: A concurrent multiscale approach for metals—$29,184

California State University, Northridge
Thomas Minehan, Department of Chemistry and Biochemistry
Indium-mediated electron-transfer to carbonyl and thiocarbonyl compounds: Exploring the synthetic potential of radical reactions in aqueous media—$35,218

California State University, Sacramento
Katherine D. McReynolds, Department of Chemistry
Synthesis of novel anionic glycodendrimers and evaluation of their anti-viral properties—$41,220

Centenary College of Louisiana
Joshua D. Lawrence, Department of Chemistry
Trifluoromethylation of aromatic compounds via C-H activation using iron reagents—$40,171

Coastal Carolina University
John Alan Goodwin, Department of Chemistry and Physics
Immobilized iron porphyrins in catalytic peroxynitrite decomposition—$45,800

Colgate University
Enrique J. "Kiko" Galvez, Department of Physics and Astronomy
Optical singularities in high-order modes of gaussian beams—$36,411

College of Wooster
Paul A. Bonvallet, Department of Chemistry
The synthesis, characterization, and supramolecular properties of a light-emitting polymer—$36,232

Creighton University
James T. Fletcher, Department of Chemistry
Shape-persistent oligoarenes possessing peptidomimetic properties—$36,827

Creighton University
Mark A. Freitag, Department of Chemistry
The effect of solvation on the Mannich reaction: An ab initio, density functional theory and QM/MM study—$33,468

Denison University
Daniel C. Homan, Department of Physics and Astronomy
Investigating the circular polarization of extragalactic radio jets—$23,700

Drake University
Charles Nelson, Department of Physics and Astronomy
Circumnuclear dynamics of the host galaxies of active galactic nuclei—$30,226

Franklin and Marshall College
John Kenneth Krebs, Department of Physics and Astronomy
Optical spectroscopy of lanthanide impurities in sol-gel yttrium oxide nanoparticles—$41,822

Franklin and Marshall College
Andrea N. Lommen, Department of Physics and Astronomy
The pulsar timing array: A nanoHertz gravitational wave detector—$36,982

Franklin and Marshall College
Ryan A. Mehl, Department of Chemistry
Generation and evaluation of improved site-specifically incorporated photocrosslinking amino acids for in vivo membrane studies—$39,704

Hamilton College
Seth A. Major, Department of Physics
Discrete geometry phenomenology and an inner product for cosmology—$26,032

Harvey Mudd College
Vatche Sahakian, Department of Physics
Aspects of non-commutative geometry—$32,058

Harvey Mudd College
David A. Vosburg, Department of Chemistry
Biomimetic cyclization cascades to form endiandric acid natural products—$35,683

Haverford College
Alexander J. Norquist, Department of Chemistry
Directed synthesis of noncentrosymmetric materials—$36,704

Hofstra University
Gregory C. Levine, Department of Physics
Entanglement entropy in impure condensed matter—$23,684

Houghton College
Mark E. Yuly, Department of Physics
An experimental search for pre-existing nuclear Δ^{++} components using the ^{3}He(n,2p) reaction—$35,888

Illinois State University
David L. Cedeno, Department of Chemistry
Effects of molecular structure and environment on photophysical and photochemical properties of novel photosensitizers—$34,176

Illinois State University
Epaminondas Rosa Jr., Department of Physics
Synchronous transitions in plasmas with noncoherent and competing signals—$33,122

Illinois Wesleyan University
Linda M. French, Department of Physics
Physical studies of primitive solar system bodies—$34,018

Indiana University-Purdue University, Fort Wayne
Desiderio A. Vasquez, Department of Physics
Chemical pattern formation induced by shear flow—$43,099

James Madison University
Kathryn A. Layman, Department of Chemistry
Spectroscopic investigation of catalytic solid-liquid interfaces—$38,951

James Madison University
Scott Paulson, Department of Physics
Electrical properties of CVD grown double-walled carbon nanotubes—$41,651

Lewis and Clark College
Nikolaus M. Loening, Department of Chemistry
The development and characterization of chemical shift thermometers for nuclear magnetic resonance spectroscopy—$39,968

Loyola University
Armin Kargol, Department of Physics
Novel voltage protocols and analysis methods for the non-equilibrium response spectroscopy of voltage-gated ion channels—$39,218

Marist College
John Morrison Galbraith, Department of Chemistry and Physics
Valence bond studies of transition metal dioxygen bonding: A key intermediate in enzymatic reactions and catalysis—$35,718

Marquette University
Christopher J. Stockdale, Department of Physics
Direct proof for the delayed formation of stellar mass black holes: A radio study of supernova 2001em—$29,024

McPherson College/Southwestern Oklahoma State University
Timothy J. Hubin, Department of Chemistry
Antiviral bridged macrocycle derivatives and metal complexes: CXCR4 co-receptor antagonists—$44,218

Miami University
Samir Bali, Department of Physics
Investigation of radiative interactions and quantum tunneling in optical lattices by correlation measurement of the scattered light—$38,838

Middlebury College
Noah Graham, Department of Physics
Quantum Z-strings and oscillons in the electroweak standard model—$33,720

Missouri State University
Nikolay Nikolaevich Gerasimchuk, Department of Chemistry
Visible light insensitive silver(I) cyanoximates—$30,996

COTTRELL COLLEGE SCIENCE AWARDS (continued)

Montclair State University
Jeffrey H. Toney, Department of Chemistry and Biochemistry
An interdisciplinary study of the beneficial effects of peanuts in preventing onset of type 2 diabetes—$44,176

Mount Saint Vincent University
Aibing Xia, Department of Chemistry
Synthesis and catalytic applications of novel bidentate N-heterocyclic carbenes (NHCs) in aerobic oxidation of alcohols—$37,665

Oakland University
George B. Martins, Department of Physics
Strong correlation effects in transport properties of carbon nanotubes—$44,996

Oberlin College
Jason M. Belitsky, Department of Chemistry and Biochemistry
Aminooxy serine/threonine peptide ligation—$45,640

Occidental College
Aram M. Nersissian, Department of Chemistry
Structural and mechanistic characterization of Factor VIII, the causative agent of Hemophilia A—$36,676

Pacific University
James J. Butler, Department of Physics
Investigation of the nonlinear optical properties of capillary waveguides and waveguide arrays at infrared wavelengths—$39,984

Saint Louis University
Michael A. Lewis, Department of Chemistry
Effects of substitution on arene-arene interactions—$43,086

Saint Louis University
Brent M. Znosko, Department of Chemistry
Thermodynamic and structural characterization of short RNA oligomers containing inosine—$45,068

Sam Houston State University
C. Renee James, Department of Physics
The Carina Dwarf Spheroidal: The rosetta stone for dwarf galaxy evolution—$41,778

San Diego State University
Fridolin Weber, Department of Physics
Cooling behavior of rotating neutron stars—$30,379

San Francisco State University
Scott Gronert, Department of Chemistry and Biochemistry
Mass spectrometric analysis of protein carbonylation from oxidative stress—$38,000

San Francisco State University
Bruce A. Manning, Department of Chemistry and Biochemistry
Surface chemistry and remediation reactions of nanometer scale metallic iron paticles—$37,800

Seattle University
Peter J. Alaimo, Department of Chemistry
Synthesis of novel N-heterocycles via tandem indium(0)-indium(III)-mediated reactions—$41,218

Seton Hall University
M. Alper Sahiner, Department of Physics
Pulsed laser deposition and structural and electrical characterization of high-k dielectric films for the replacement of SiO^2 in CMOS gate region—$32,574

Sonoma State University
Jennifer Whiles Lillig, Department of Chemistry
Characterization of key amino acids in the membrane activity of anti-Listerial bacteriocins—$34,895

Southwest Missouri State University
Gary A. Meints, Department of Chemistry
Investigating local dynamics in damaged DNA via solid-state deuterium NMR—$35,684

Swarthmore College
Thomas A. Stephenson, Department of Chemistry and Biochemistry
Inelastic collision dynamics in the O + NO system: Rotational and spin-orbit distributions—$35,000

Texas A&M University at Commerce
Anil R. Chourasia, Department of Physics
Chemical reactivity at Hf/SiO_2 interface—$43,650

Texas State University, San Marcos
Rachell E. Booth, Department of Chemistry and Biochemistry
An investigation into subunit-subunit interactions within the epithelial sodium channel (ENaC)—$34,738

Trinity University
Adam R. Urbach, Department of Chemistry
Cofactor-modulated recognition of peptides in aqueous solution by a synthetic host—$38,880

Truman State University
Maria C. Nagan, Department of Chemistry
Molecular dynamics studies of human immunodeficiency virus Rev-RRE recognition—$35,400

University of Colorado at Colorado Springs
Radek Lopusnik, Department of Physics and Energy Science
Time- and frequency-domain investigations of thermally excited spin waves in ferrite and magnetic metallic films—$43,683

University of Colorado at Colorado Springs
David J. Weiss, Department of Chemistry
The chemistry of enzyme sensor microchip—$40,500

University of Memphis
Sanjay R. Mishra, Department of Physics
On the magnetic properties of rare-earth oxide coated ferromagnetic nanoparticles—$40,218

University of Minnesota, Duluth
Steven M. Berry, Department of Chemistry
New mixed-valence dinuclear lanthanide complexes— $35,144

University of Minnesota, Duluth
Leng Chee Chang, Department of Chemistry
Inhibition of aerial hyphae formation in streptomyces sp. to search for protein kinase inhibitors—$39,718

University of Minnesota, Duluth
Josef P. Werne, Department of Chemistry
Response of terrestrial vegetation in tropical East Africa to temperature, aridity, and pCO_2: A molecular isotopic approach—$39,543

University of Northern Iowa
Robert Martin Chin, Department of Chemistry
Di and trinuclear polyhydride transition metal complexes containing a rigid cyclopentadienyl framework—$33,118

University of Puget Sound
Christine M. Smith, Department of Chemistry
Investigating in vivo targets of histone acetylases and deacetylases using isotopic labeling and tandem mass spectrometry—$32,306

University of San Diego
Jeremy Kua, Department of Chemistry
Preliminary steps toward simulating self-assembly of metal-organic frameworks—$37,348

University of San Diego
Michelle D. Chabot, Department of Physics
Investigation of individual submicron magnetic structures at room temperature using micromechanical cantilever magnetometry—$37,950

University of Scranton
John C. Deak, Department of Chemistry
Mechanisms of vibrational energy transfer through self-assembled molecular aggregates—$36,218

University of Texas at Brownsville
Soumya Darshan Mohanty, Department of Physics and Astronomy
Improved hierarchical search algorithms for gravitational wave data analysis—$22,400

University of Vermont
Sanjeeva Murthy, Department of Physics
Modification of the structure of polymer surfaces to control and direct cell growth—$37,052

University of Wisconsin, Eau Claire
Alan Gengenbach, Department of Chemistry
Metalloporphyrin catalyzed oxidation of azo dyes—$34,876

University of Wisconsin, La Crosse
John S. Colton, Department of Physics
T_2 measurements in GaAs, AlGaAs, and InGaAs layers and quantum wells via optically detected electron spin echo—$21,853

University of Wisconsin, La Crosse
Shauna Sallmen, Department of Physics
Study of interstellar shells in our galaxy—$27,418

Wellesley College
Mark S. Goldman, Department of Physics
Computational modeling of the neural basis of a visual masking illusion—$36,461

West Texas A&M University
Mark Olsen, Department of Math and Physical Science
Directed evolution of chondroitinase B using flow cytometry and cell surface display technology—$35,218

Western Kentucky University
Kevin M. Williams, Department of Chemistry
Cleavage of proteins by bulky platinum complexes—$29,576

Western Washington University
Takele Seda, Department of Physics and Astronomy
Low-temperature ^{57}Fe Mossbauer studies of the magnetic and electronic properties of nanomagnetic iron (oxy)hydroxides—$34,064

Western Washington University
Mark L. Wicholas, Department of Chemistry
Bonding modes of isoindoline pincer ligands in transition metal complexes: Studies in zwitterion formation and C-H activation—$47,468

Williams College
Amy Gehring, Department of Chemistry
Biochemical characterization of the WhiJ sporulation proteins from Streptomyces coelicolor—$41,219

Xavier University, Cincinnati
Richard J. Mullins, Department of Chemistry
Synthesis and medicinal chemistry of kalkitoxin, a secondary metabolite of Lyngbya majuscula—$35,754

Xavier University, Cincinnati
Heidrun Schmitzer, Department of Physics
Investigation of the feasibility of selfadjusting optical elements on the basis of angular momentum transfer at the end of an optical fiber—$40,720

COTTRELL SCHOLAR AWARDS

Massachusetts Institute of Technology
Eric W. Hudson, Department of Physics
Searching for hidden order in exotic superconductors by scanning tunneling microscopy—$100,000

Miami University
Hongcai Zhou, Department of Chemistry and Biochemistry
Hydrogen storage in novel C-N based porous materials—$100,000

New York University
Paramjit S. Arora, Department of Chemistry
Control of protein-protein interactions with artificial alpha helices and innovations in the teaching and implementation of organic chemistry—$100,000

Northwestern University
Teri W. Odom, Department of Chemistry
Nanoscaffolds for the growth and manipulation of chemical and biological structures at the single component-level—$100,000

Southern Illinois University at Carbondale
Boyd M. Goodson, Department of Chemistry and Biochemistry
Enhancing NMR signals from biomolecular, organic and polymer thin films using optical nuclear polarization—$100,000

Tulane University
Zhiqiang Mao, Department of Physics
Studies of metamagnetic quantum critical phenomena in ruthenates—$100,000

University of Chicago
Chuan He, Department of Chemistry
A chemical crosslinking method to study DNA repair/modification proteins—$100,000

University of Illinois at Urbana-Champaign
Chad M. Rienstra, Department of Chemistry
Science beyond the limits of diffraction and disciplinary borders: 3D magic-angle spinning NMR and the liberal arts—$100,000

University of Missouri-Rolla
Thomas Vojta, Department of Physics
Disordered electronic quantum phase transitions and an interactive approach to teaching computational physics—$100,000

University of Montreal
Pierre Bergeron, Department of Physics
White dwarf stars as cosmochronometers and distance indicators—$100,000

University of Ottawa
Keith Fagnou, Department of Chemistry
Preventing catalyst decomposition and achieving reactivity in the direct arylation and animation of C-H bonds—$100,000

University of Wisconsin, Madison
Helen E. Blackwell, Department of Chemistry
Regulation of bacterial communication pathways with synthetic ligands—$100,000

University of Wisconsin, Madison
Gary Shiu, Department of Physics
Connecting string theory to experiment—$100,000

RESEARCH OPPORTUNITY AWARDS

Portland State University
Carl C. Wamser, Department of Chemistry
Nanostructured material for solar energy conversion: Photoconductive porphyrin polymers—$50,000

University of Miami
Joshua Lawrence Cohn, Department of Physics
Dielectric studies of low-dimensional and competing-order ground states in transition-metal oxides—$50,000

University of Minnesota, Twin Cities
Doreen Geller Leopold, Department of Chemistry
Anion photoelectron spectroscopy of transition metal clusters and metal-ligand complexes—$50,000

University of Rochester
Frank L.H. Wolfs, Department of Physics
Pushing the dark-matter limit: R&D for Zeplin IV—$50,000

University of Wisconsin, Madison
Michael J. Winokur, Department of Physics
Computer modeling of conducting polymer microstructures and the influence of templating interfaces—$50,000

Research Corporation's condensed financial statements of financial position and activity for the years ended December 31, 2005 and 2004 are presented in this section.

The foundations audited financial statements for 2005 and 2004 can be viewed online at www.rescorp.org/finanacials

Condensed Statements of Activity and Changes in Net Assets

YEARS ENDED DECEMBER 31, 2005 AND 2004

	2005	2004
REVENUES		
UNRESTRICTED REVENUES AND INCOME		
Investment income, net	$17,581,151	$15,801,148
Other income	107,780	11,100
Total unrestricted revenues and income	17,688,931	15,812,248
Contributions released from restrictions	0	250,000
TOTAL REVENUES	17,688,931	16,062,248
EXPENSES		
Grants approved	5,622,515	4,954,942
Science advancement	1,291,357	1,392,532
Program-related	1,886,076	475,875
Information and communication	209,744	192,085
General and administrative	1,736,659	1,822,190
Interest and other expense	120,258	387,918
TOTAL EXPENSES	10,866,609	9,225,542
INCREASE IN UNRESTRICTED NET ASSETS	6,822,322	6,836,706
DECREASE IN TEMPORARILY RESTRICTED NET ASSETS	0	-250,000
INCREASE IN NET ASSETS	6,822,322	6,586,706
NET ASSETS – Beginning of the Year	141,687,829	135,101,123
NET ASSETS – End of the Year	**$148,510,151**	**$141,687,829**

Condensed Statements of Financial Position

DECEMBER 31, 2005 AND 2004

	2005	2004
ASSETS		
INVESTMENTS	$146,061,571	$141,712,969
Cash and cash equivalents	663,103	118,338
Restricted cash	0	1,028,880
Accrued dividends and interest receivable	328,282	317,012
Other receivables	828,876	702,000
Notes receivable	5,986,437	7,594,674
Property and equipment, net	491,697	424,045
Interest in LLC	1,951,071	2,131,500
Prepaid pension cost	914,468	1,143,780
Other assets	67,525	64,525
TOTAL	**$157,293,030**	**$155,237,723**
LIABILITIES AND NET ASSETS		
LIABILITIES		
Grants payable	$4,747,679	$4,556,243
Line of credit	0	4,500,000
Notes payable	1,294,925	2,300,000
LBT payable	1,427,766	634,000
Other	1,312,509	1,559,651
TOTAL LIABILITIES	8,782,879	13,549,894
UNRESTRICTED NET ASSETS	148,510,151	141,687,829
TOTAL	**$157,293,030**	**$155,237,723**

Officers

Herbert S. Adler, Chairman of the Board

James Gentile, President

Raymond Kellman, Vice President

Suzanne D. Jaffe, Treasurer

Robert B. Hallock, Secretary

Daniel Gasch, Chief Financial Officer and Employee Benefits Plan Administrator

Board of Directors

Herbert S. Adler is President of Halcyon Management Co. LLC. He is a member of the Research Corporation Executive Committee, Finance Committee, Science Advancement Committee, Audit Committee and Employee Benefits Committee.

Patricia C. Barron is a Corporate Director. She is a member of the Research Corporation Finance Committee and Science Advancement Committee.

Stuart B. Crampton is the Barclay Jermain Professor of Natural Philosophy in the Department of Physics at Williams College. He is a member of the Research Corporation Executive Committee, Finance Committee and Science Advancement Committee.

Peter K. Dorhout is Vice Provost for Graduate Studies, Assistant Vice President for Graduate Studies and Professor of Chemistry at Colorado State University. He is a member of the Research Corporation Science Advancement Committee and Governance and Nominating Committee.

James M. Gentile is President of Research Corporation. He is a member of the Executive Committee and the Science Advancement Committee.

Robert B. Hallock is Distinguished Professor in the Department of Physics at the University of Massachusetts at Amherst. He is a member of the Research Corporation Science Advancement Committee.

Robert Holland Jr. is an Industry Partner with Williams Capital Partners.He is a member of the Research Corporation Executive Committee, Finance Committee, Science Advancement Committee, Audit Committee and Governance and Nominating Committee.

Brent L. Iverson is a Professor of Chemistry and Biochemistry at University of Texas at Austin. He is a member of the Science Advancement Committee.

Gayle P.W. Jackson is Managing Director of FE Clean Energy Group Inc. She is a member of the Research Corporation Finance Committee and Science Advancement Committee.

Suzanne D. Jaffe is President of S.D.J. Associates. She is a member of the Research Corporation Executive Committee, Finance Committee, Science Advancement Committee and Governance and Nominating Committee.

Patrick S. Osmer is Chair and Distinguished Professor in the Department of Astronomy at Ohio State University. He is a member of the Research Corporation Finance Committee, Governance and Nominating Committee and Science Advancement Committee.

John P. Schaefer is President of the LSST Corporation. He is a member of the Research Corporation Finance Committee and Science Advancement Committee.

Directors Emeriti

R. Palmer Baker Jr. is President of the Baker Company, Inc.

Carlyle G. Caldwell is Chairman Emeritus, National Starch and Chemical Corporation

Paul J. Collins is Vice Chairman of Citibank.

Helen Day is Secretary Emeritus of Research Corporation.

Burt N. Dorsett is Chairman of the Board of Dorsett McCabe Capital Management Inc.

William G. Hendrickson is Chairman Emeritus of St. Jude Medical Inc. and Chairman of IntelliNet.

John W. Johnstone Jr. is Chairman of the Governance and Nominating Committee at Arch Chemicals Inc.

Frederick Seitz is President Emeritus of The Rockefeller University.

George L. Shinn is Chairman and Chief Executive Officer Emeritus of The First Boston Corporation.

G. King Walters is the Sam and Helen Worden Professor of Physics at the Department of Physics and Astronomy at Rice University. He is a member of the Research Corporation Executive Committee and Science Advancement Committee.

Program Advisory Committee

James Gentile is Chairman of the Program Advisory Committee and President of Research Corporation.

Mark E. Bussell is a Professor of Physical Chemistry at Western Washington University.

Donald R. Deardorff is a Professor of Chemistry at Occidental College.

Susan M. Kauzlarich is a Professor of Chemistry at University of California, Davis.

John Koh is an Associate Professor of Chemistry & Biochemistry at the University of Delaware.

Elizabeth McCormack is an Associate Professor of Physics at Bryn Mawr College.

Michael A. Morrison is a Professor of Physics and General Education at the University of Oklahoma.

Mats A. Selen is a Professor of Physics at the University of Illinois at Urbana-Champaign.

Thomas D. Tullius is a Professor of Chemistry at Boston University.

Research Corporation Personnel

James Gentile, President

Raymond Kellman, Vice President

Jack R. Pladziewicz, Program Officer

Leon Radziemski, Program Officer

Silvia Ronco, Program Officer

Brian Andreen, Consultant

Linda Neefe, Executive Assistant to the President

Patricia Maguire, Executive Assistant to the Vice President

Christina A. Adams, Program Assistant

Pamela Busse, Program Assistant

Sandy Champion, Program Assistant

Brenda Sheehy, Program Assistant

Sofia Fontana, Office Coordinator

Tommy Goodenow, System Administrator

Dena McDuffie, Editor & Archivist

Randy Wedin, Science Writer

Kelly Leslie, Designer

Page 5.
Walls of ice, such as the outer margin of Mt. Kilimanjaro's ice sheet shown here, are retreating across the globe. Societal problems, such as climate change, will be important drivers for interdisciplinary scientific research in the coming decades. Photo by Lonnie G. Thompson, Ohio State University.

Page 6.
American postage stamp commemorating the fall of the Berlin Wall. Courtesy of the Postal History Foundation, Tucson, Arizona.

Page 7.
A hedge maze viewed obliquely from above. IStock photo, copyright Andrew Green.

Page 8.
Walls can be beautiful—and useful. The silicate cell walls that encase diatoms, such as those shown here, display jewel-like symmetry. Today, scientists are using molecular biology, inorganic chemistry, and computer modeling to coerce these unicellular algae to produce miniature devices for electronic and optical applications. Photo by Hans Paerl, courtesy of University of North Carolina's *Endeavors* magazine.

Page 9.
Stone wall in Mexico. Photo courtesy of Dena McDuffie

Page 10.
"The Battering Ram in Combat" by Andreas Cellarius, from *Architectura Militaris*, 1645.

Page 11.
Person climbing a stone wall in Barcelona. IStock photo, copyright Martin Garnham.

Page 12.
Cartoon courtesy of ScienceCartoonsPlus.com

Page 13.
Boundaries between liquids, like boundaries between disciplines, are dynamic. This colored interferometric picture illustrates evolving patterns formed during the spreading of a surface-active substance over a thin liquid film on a silicon wafer. The study of micro- and nano-fluidics is leading to the development of miniature devices for manipulating small-scale liquid structures. "Liquid Fractals in Spreading Surfactant Films" by A.A. Darhuber (Virginia Polytechnic Institute and State University, Blacksburg, Virginia), B.J. Fischer (ExxonMobil, Houston, Texas) and S.M. Troian (California Institute of Technology, Pasadena, California) Contact: stroian@caltech.edu

Page 14.
The Great Wall of China was built to protect the various dynasties from raids by nomadic tribes coming from areas in modern-day Mongolia and Manchuria. The wall is the world's longest man-made structure, stretching over 3,948 miles. Mao Tse-Tung had a saying which translates roughly as "You're not a real man if you haven't climbed the Great Wall." Istock photo, copyright Eugenia Kim.

Page 15.
The Humpty Dumpty riddle first appeared in print in 1810. He appears in Lewis Carroll's *Through the Looking-Glass*, where he discusses semantics and pragmatics with Alice. "When I use a word," Humpty Dumpty said, in rather a scornful tone, "it means just what I choose it to mean—neither more nor less."

Page 16.
At the end of the sixth century, St. John Climacus renounced Earthly ways and chose instead to dedicate himself to God. He wrote the famous spiritual classic *The Ladder of Divine Ascent* which describes thirty stages of spiritual development, which Climacus likened to thirty steps up a ladder. The steps led the spiritual striver to salvation—the ultimate goal of spiritual struggle. This concept is depicted graphically as a stairway from earth to heaven.

Page 17.
Cartoon courtesy of ScienceCartoonsPlus.com

Page 18.
Ground was broken for construction of the Brooklyn Bridge on January 3, 1870. The bridge crosses the East River between Brooklyn and lower Manhattan. When the bridge was being planned, Brooklyn was a small, rural community. The city of New York—which at the time consisted only of Manhattan—had twice as many residents and the bridge was seen as a solution to overcrowding in Manhattan while spurring development in Brooklyn. Photo courtesy of Dena McDuffie.

Page 19.
Walls are getting smaller and smaller. In the past decade, single-walled carbon nanotubes have generated intense research activity by chemists, physicists, and material scientists. With nanotubes' extraordinary mechanical and electronic properties, scientists envision a multitude of applications. This image simulates the view from within a flattened, twisted carbon nanotube only six atoms across. Courtesy of Vin Crespi, Pennsylvania State Physics. Distributed under the Creative Commons license creativecommons.org/licenses/by-sa/2.0

Page 20.
A circular stairway viewed from above. IStock photo, copyright Sorin Brinzei.

Page 21.
Nature devises clever ways to pass through walls. The membrane proteins that allow water to pass selectively through cell walls were only recently identified. The 2003 Nobel Prize in Chemistry, recognizing Peter Agre's discovery of aquaporins, exemplifies how chemistry's molecular approach can answer biological questions. In this simulation, water molecules flip as they march through the aquaporin's narrow pore. Courtesy of Emad Tajkhorshid and Klaus Schulten, Theoretical and Computational Biophysics Group, University of Illinois at Urbana-Champaign.

Page 22.
Mexican lotteria (lottery) dates to the late 1800s. It is similar to Bingo, but instead of numbers, images like the sun, the musician, the watermelon—and the ladder—are used.

Page 23.
Ladder at a monastery in Santorini, Greece.

Page 24.
"Wall in the Grand Cañon, Colorado River" by Timothy H. O'Sullivan, 1871. O'Sullivan was a photographer for the Geological Exploration of the Fortieth Parallel, the first survey of the American West.

Page 25.
Overlooking Golden Gate Bridge, Sutro Heights Park, San Francisco. Istock photo, copyright Teresa Hurst.

Page 26.
Dynamic interaction at the interface—between lava and seawater (or between scientific disciplines)—can release great amounts of heat, light, and energy. Eventually the interaction cools, resulting in the formation of new land, new walls, and new barriers. In this photo, rivers of lava from the volcano Kilauea in Hawaii leave a lava tube at a bench of new land at the Ka`ili`ili sea. Photo by Tom Pfeiffer/www.decadevolcano.net/VolcanoDiscovery.com

Page 28.
Line of stepping stones across river. The bed of the river can be seen through the shallow water. IStock photo, copyright Malcolm Romain.

Page 30.
Cech photo by Paul Fetters for HHMI. Ellis photo courtesy of University of California at San Diego. Keller photo courtesy of University of Minnesota's Humphrey Institute. Kopell photo courtesy of Boston University. Onuchic photo courtesy of University of California at San Diego. Stevens photo courtesy of the Salk Institute.

Research Corporation

4703 East Camp Lowell Drive
Suite 201
Tucson, Arizona 85712
www.rescorp.org