Facilitating Interdisciplinary Research and Education: A Practical Guide

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Acknowledgments

This guide reflects the combined wisdom of all who participated in the workshop "Science on FIRE: Facilitating Interdisciplinary Research and Education," held March 28-29, 2011, hosted by the American Association for the Advancement of Science and the Colorado Initiative in Molecular Biology of the University of Colorado, Boulder. The editors express their deep appreciation to the participants and especially to Steve Olson for his efforts in combining the information gathered at the workshop into a coherent document. AAAS is grateful to the Research Corporation for Science Advancement for its generous support of the production of this guide.

Preface

The scientific community is talking about the need to embrace interdisciplinary research and education. Many individuals, programs, and institutions have made great advances in developing a variety of interdisciplinary approaches, but systemic progress has been slow.

The need to accelerate the adoption of interdisciplinary approaches is even more compelling in an era with increasingly complex problems, vast data sets, and powerful research tools. Many of the most interesting and important problems in science can be answered only through collaborative efforts. The increasing complexity of science demands that concepts and methods from different disciplines be merged. Calls for science to contribute even more substantially to human well-being re-emphasize that interdisciplinary research can no longer be an optional pursuit -- it must be front and center in any discussion of the future of science.

On March 28-29, 2011, the American Association for the Advancement of Science and the University of Colorado Biofrontiers Institute hosted a workshop entitled *"Science on FIRE: Facilitating Interdisciplinary Research and Education."* The workshop brought together more than 150 practitioners, administrators, and funders of interdisciplinary research to identify keys to success and strategies for overcoming barriers. Interdisciplinary approaches are necessarily varied, based on the problem being studied, the institution doing the research, and the individuals involved in the projects. Every project offers broader lessons. The workshop sought to distill these lessons into principles that anyone can use.

The workshop was more than a collection of success stories. Participants spoke frankly about the challenges they have faced and the disappointments they have endured. The incentive and reward systems within many institutions continue to discourage collaboration. Scientific disciplines have different cultures, languages, and standards. Most classes at the undergraduate and graduate levels remain limited by disciplinary boundaries. The workshop participants were not pessimistic about the challenges – they found them barriers to be overcome.

This document, which has been drawn from the presentations and discussions at the workshop, has been written for anyone involved with or interested in interdisciplinary research and education, including funders, administrators, researchers, faculty, and students. It is a practical guide to motivating, organizing, and establishing interdisciplinary programs. It also discusses broad issues that transcend individual programs. This report features descriptions of current programs in sidebars as examples, but not necessarily as models to copy, since every institution and program is different. Some of the information in this guide is basic, and some involves the detailed steps of setting up an interdisciplinary program or center. At the end of each chapter there are suggestions for additional reading and other resources available in print and online.

The *"Science on FIRE"* workshop was designed to be thought-provoking and provocative. It turned out to be extremely productive as well. We hope that the lessons gleaned from the conversation will help interdisciplinary programs achieve the prominence they need and deserve.

Tom Cech, University of Colorado Biofrontiers Institute
Alan Leshner, American Association for the Advancement of Science

The Imperative for Interdisciplinary Research

The most important problems confronting science and society cannot be solved by researchers in individual scientific disciplines working in isolation.

- How can human societies generate enough energy to meet human needs without doing irreparable harm to the earth?
- How do individual DNA sequences interact with environmental inputs to influence the incidence of disease?
- How does the passage of electrical signals among neurons in the human brain generate such a subtle and complex array of behaviors?
- How will changes in the earth's atmosphere affect climate, glaciers, and the oceans?
- What combination of biological, environmental, and social factors accounts for the increase in obesity rates observed in many parts of the world?
- How can innovations in agriculture feed a growing human population?

These and many other scientific problems are inherently interdisciplinary. They require the collaborative efforts of scientists who have different backgrounds, knowledge, perspectives, and expertise.

Interdisciplinary research is as varied as its subject matter. Interdisciplinary teams differ in size, composition, organization, and location. They have diverse goals, ranging from basic scientific discoveries to the development of applied technologies. Some are small, local, and informal; others are large, transnational, and carefully structured. Often, members of a collaborative team contribute diverse disciplinary approaches. Alternatively, an individual who understands methods and theories across more than one discipline can pursue interdisciplinary approaches. The lessons derived from interdisciplinary research often depend on the context of that research, as does the application of those lessons.

Interdisciplinary research will add new facets to research and make institutions, individual researchers, and disciplinary understanding even stronger. Traditional academic disciplines carve out particular areas of knowledge and try to understand those features as deeply as possible. Interdisciplinary research asks how these disciplinary understandings can be merged, expanded, and transcended. Interdisciplinary research will continue to require concepts and methods developed through disciplinary research, but it will integrate that knowledge to create new connections between disciplines and new explanations of complex phenomena. At its best, interdisciplinary research creates knowledge that no single discipline can create on its own.

The one thing that interdisciplinary research shares is a sense of tremendous potential. The biosciences are a good example. Last year, more DNA was sequenced in one year than in all of previous history. Yet the number of new pharmaceuticals approved to treat diseases has if anything undergone a slight downward trend. Interdisciplinary research will be essential to create new paths between fundamental understandings and practical applications. By combining subdisciplines of biology with aspects of physics, chemistry, computer science, and engineering, an interdisciplinary approach to the biosciences will produce new knowledge that could not only improve health but meet human needs in such areas as energy, agriculture, and environmental sustainability.

The complex challenges that affect human well-being will not be solved without unleashing the potential inherent in interdisciplinary research. It is inevitable that interdisciplinary research will become a larger and more prominent component of the scientific enterprise.

The Effects of Technology on Research Practices

The rapid development and dissemination of digital technologies have helped to enable interdisciplinary research. First, digital technologies make it possible to generate and analyze immense quantities of data. They create new capabilities for juxtaposing information and ideas. Interpreting large and complex databases almost always requires the contributions of multiple disciplines and subdisciplines. However, capabilities to generate vast amounts of data can also widen the gap between data and knowledge and between knowledge and understanding.

Second, electronic networks are making it much easier for investigators from different fields to communicate and collaborate. Researchers can access literature in other fields, share data with ease, and communicate rapidly with potential collaborators anywhere in the world. Electronic social networks, new forms of communication such as texting, approaches to knowledge generation like crowdsourcing, and electronic capabilities available through phones and other personal devices are giving people new ways of working together -- especially young people who have grown up with these technologies.

These rapid changes in science are pointing toward a very different model for scientific research. In the future, science could become much more open, distributed and collaborative. The basic system that produces, shapes, and uses scientific knowledge may be changing, though the outcomes of those changes are difficult to foresee. Traditional academic structures, which today are organized largely by disciplinary boundaries, could begin to crumble as disciplines converge. Research topics like nanobiotechnology require a coherent and compatible approach but do not fit within any traditional academic discipline. Researchers, administrators, and funders face a great challenge in responding to this onslaught of largely unpredictable change.

Defining Terms

Today there are still a number of different definitions for the terms interdisciplinary, multidisciplinary, transdisciplinary, cross-disciplinary, or post-disciplinary. Speakers at the symposium generally used the term "interdisciplinary" to represent all of the above terms[1].

[1] The National Academies has defined interdisciplinary research as "a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice." -Committee on Facilitating Interdisciplinary Research, Committee on Science, Engineering, and Public Policy (2004). *Facilitating interdisciplinary research*. National Academies. Washington: National Academy Press, p. 2.

Peter Bruns, former Vice President for Grants and Special Programs at the Howard Hughes Medical Institute, offered a provocative metaphor to describe the difference between multidisciplinary and interdisciplinary.

If each discipline were represented by a different type of vegetable, then *multidisciplinary* work would be the equivalent of a salad bar: the disciplines combine to create something larger, and usually more interesting, but each part is still easily recognized by its distinct appearance and flavor. In contrast, *interdisciplinary* work is more like V8 juice, in which the disciplines are broken down and recombined to yield something with properties quite distinct from its original components.

***"Science is changing at an increasing rate. It is becoming, by any reasonable argument, more and more interesting and more and more powerful."* -- David Botstein**

***"The barriers to individual faculty collaborating with each other are really quite low. Faculty like to talk to each other, and when they find that they can help each other, they set up a collaboration. But as soon as you want to set up a program that grants a degree or hires faculty or grants promotion with tenure, then you end up with a number of challenges."* -- Tom Cech**

Barriers to Overcome

At the symposium, Tom Cech, Director of the University of Colorado Biofrontiers Institute, listed some of the statements he has heard over the years that can stall interdisciplinary research and education.

"We can't support people for promotion with tenure who have been middle author on most of their papers."

"The university does not allow grad students to apply directly to an interdisciplinary program, only to departments."

"Our department isn't interested in providing financial support, because we could end up putting in more than we get out."

"Tuition in our college is higher, so there's no way for students from your college to take our courses for credit."

"Our college defines a graduate course as having more than 40 students, so we couldn't give our faculty credit for teaching in your 20-student interdisciplinary graduate course."

"Our department couldn't give a Ph.D. in ___ to these interdisciplinary students, because they'd end up having only two courses in ____ and we require three."

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Creating an Interdisciplinary Culture

Most of today's researchers were educated in and have worked in largely disciplinary cultures. Therefore, successful interdisciplinary research typically requires explicitly creating and sustaining an interdisciplinary culture. Ultimately, the success of any interdisciplinary pursuit depends on the people engaged in that research; but people can be placed in circumstances that are more or less conducive to interdisciplinary success.

Balancing Tensions

Ed Hackett, a sociologist from Arizona State University who studies the social organization of science, offered a theoretical perspective on creating an interdisciplinary structure. The culture of science is in many ways a culture of contradictions. Rather than forging compromises between extremes, creativity and achievement often flourish in the presence of antagonists. Some of these tensions include:

- Originality↔Tradition
- Disinterestedness↔Passion
- Cooperation↔Competition
- Closing↔Opening
- Sharing↔Secrecy
- Distinctiveness↔Belonging
- Engagement↔Independence
- Autonomy↔Accountability
- Democracy↔Autocracy

From this perspective, interdisciplinary research requires making choices about how to balance these tensions, which may differ from established disciplinary practices. Achieving this new balance may not be easy. Disciplines often have distinct cultures and different ways of doing science. A descriptive discipline, such as paleontology, applies different standards to research than does a discipline based on experimentation or theory. Publication practices, data-sharing traditions, and even some of the subtleties of scientific ethics and standards can vary across fields. For example, who should be considered an author of a paper, and how are authors listed? How many classes do students take per semester, and how many classes do faculty teach? How much are faculty, research assistants, and teaching assistants paid? Resolving differences that arise over these issues can require considerable work.

Characteristics of Individuals

Creating an interdisciplinary culture also requires making decisions about the kinds of individuals to recruit into a program. People have very different skills and reasons for doing interdisciplinary research. One approach is to attract what participants at the workshop called the 'best athlete:' -- people with a record of accomplishment who may or may not have done interdisciplinary work in the past. Another approach is to attract people who are inclined by background or temperament to excel at interdisciplinary research. In keeping with a culture of contradictions, program directors may choose to enlist both kinds of individuals in an effort to create a productive tension between their working styles.

Elements of Successful Teams

In practice, many elements must come together for interdisciplinary teams to operate successfully. Michelle Bennett, Deputy Scientific Director at the National Heart, Lung, and Blood Institute, offered the following list:

- Trust
- Membership (building a team)
- Leadership
- Shared vision
- Getting and sharing credit
- Conflict resolution
- Adversarial collaboration
- Communication and negotiation
- Team dynamics
- Team networks and surrounding systems
- Challenges to the success of scientific teams
- Fun

Bennett noted that these qualities may seem "fluffy," but they are factors that can make or break a project.

Trust

Trust is especially important for interdisciplinary research. Collaboration can be risky or threatening on both a personal and an institutional level. Participants need to be willing to sacrifice some of their independence and autonomy in favor of interdependence and group identity. They need to be able to let go of some of individual status and ego, and trust that others will do the same, in order to achieve shared goals.

Engaging in planning processes and establishing policies that lay out expectations and responsibilities can build trust. This procedural trust can, in turn, support the personal trust on which strong individual relationships are built.

Accepting Risk

Interdisciplinary research is almost always risky. Leaders of interdisciplinary projects and of institutions therefore need to learn to accept negative results as well as positive results.

Establishing a balance between positive and negative outcomes is a continual challenge. It is important to test ideas expeditiously so that failure can occur quickly rather than gradually. It also is important to convey negative results to the broader research community to add to the knowledge of what works and what does not.

Leadership

Interdisciplinary programs can form through a top-down or a bottom-up process, but in either case, institutional leadership is critical. Leaders need to bridge the differences between departments, since endless negotiations among individual faculty members can sap the energy from interdisciplinary research. Leaders help establish the physical and financial structures for cross-departmental research. They can be a force for innovation even in the midst of excellence, which is difficult but necessary in constantly changing institutions.

In all of these respects, leaders need to be able to think synthetically. Drawing on knowledge of history, literature, and philosophy, they can bring a theory of action to institutions and clarify the ever-changing present.

Leaders must be able to generate enthusiasm about the importance and science of an interdisciplinary project. They must have a big vision and pay attention to the practical details of making interdisciplinary research work. Leaders must be able to enlist the support of funders, the participation of collaborators, and the enthusiasm of students.

Leaders should emphasize the advantages of interdisciplinary research within the broader culture. The interdisciplinary approaches of these leaders can serve as an example for others. They can help to promote an interdisciplinary culture by advocating for interdisciplinary scholars, creating incentives and rewards for interdisciplinary researchers, and encouraging interdisciplinary communication. Leaders should model expected behaviors, demonstrate commitment, maintain a level playing field, and encourage good communication. They need to create an environment in which collaborators can assess projects honestly, challenge results, and talk openly about their differences. They need to foster discussion about alternative courses of action while containing conflict, which can be a difficult balancing act.

"Problem solving within social networks is increasingly common, and we can use this approach fruitfully to make funding decision and to conduct interdisciplinary research." **-- James Collins**

"Teams can be formed from the bottom up or they can be formed from the top down and be highly successful. Either way, top-down support is absolutely critical." **-- Michelle Bennett**

"The only way you can have something that will be sustainable is that you set standards and have faculty committees that are willing to maintain those standards." **-- Keith Yamamoto**

Howard Hughes Medical Institute: Janelia Farm

The Janelia Farm Research Campus is a facility built by the Howard Hughes Medical Institute on the southern bank of the Potomac River in northern Virginia. It is not affiliated with a university and thus is not subject to many of the barriers associated with interdisciplinary research, but it faced the challenge of attracting world-class researchers to a very different kind of research institution.

One way to approach the problem was to give the institution a compelling focal point. After a series of workshops, the organizers of Janelia Farm decided to focus on mapping the neural networks involved in complex behavior. To do this, the institution needed to develop new imaging devices, tools, and instruments to trace complex networks of synapses between neurons. It also needed computational tools to analyze vast amounts of information.

Janelia Farm keeps research groups small, because previous experience at places like Bell Labs has shown that having small research groups would encourage group members to pool their talents and resources. Research is internally funded so that researchers do not have to spend large amounts of time applying for grants. Janelia does not award tenure, in order to encourage cross-disciplinary approaches and a constant flow of new people and new ideas into the institution.

Janelia Farm is also designed to be an international hub for scientific meetings, workshops, and collaborations. Researchers can fly in from around the world to a fully equipped laboratory, set up a collaborative experiment, leave a student or postdoctoral fellow on site to continue the work, and fly back to their home institutions.

The architecture of the building promotes “productive collisions” in which people interact in ways that foster collaboration. The physical infrastructure of the building, including its wiring and plumbing, can easily be changed as the science evolves. Wet lab space can be converted to computational space or robotics space inexpensively. Many of the walls consist of glass to let in natural light and allow people to see what others are doing.

“HHMI had the advantage of not being a degree-granting institution or having pre-existing responsibilities, so it could start from scratch to build a home for interdisciplinary research where biologists could work shoulder to shoulder with chemists, physicists and computer scientists.” **-- Tom Cech**

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Ensuring Diversity in Interdisciplinary Research and Education

Interdisciplinary teams that include people with different backgrounds, perspectives, and ideas benefit both science and the broader society. Incorporating students, faculty, and partners from diverse backgrounds brings an array of ideas to bear on problems, broadens participation in the research enterprise, and helps prepare an innovative, diverse, and skilled workforce.

In a larger sense, all interdisciplinary collaborations are exercises in the integration of diverse people and ideas. Interdisciplinary teams will have diversity along familiar characteristics of race, ethnicity, gender, nationality, social class, and age. In addition, the people on an interdisciplinary team bring diversity based on different theoretical orientations, disciplinary cultures, types of institutions (such as hospitals and laboratories), and philosophies of science. Interdisciplinary teams can flounder unless these differences are actively addressed and managed.

Diversity and Creativity

The many parallels between interdisciplinary research and diversity in science highlight one of the great advantages of interdisciplinarity. When group members share common goals in the context of differing perspectives or skill sets, diverse groups can be more productive than more homogenous groups. Of course, better outcomes are not inevitable, but in well-managed groups, the ideas, skills, and experiences of diverse collaborators are assets that can lead to better strategies and critical insights. For this reason, large companies have made the case for diversity as an important asset for success. Academia has not done as well making the case for diversity as an asset for research outcomes.

Diverse groups are more likely to have interpersonal differences and disagreements than less diverse groups. However, a manageable level of disagreement can create the conditions for productive fusion of ideas, new insights, and expanded vision. Conflict must be managed effectively so that collaborators see each other as complementary rather than competitive. Achieving this balance requires attention to both process and management.

Recruiting and Supporting a Diverse Team

Interdisciplinary initiatives may help an institution to increase diversity. Data suggest that women and minorities are disproportionately drawn to interdisciplinary programs over disciplinary programs. For example, the evaluation of NSF's Science and Technology Centers described in the chapter on "Measuring the Outcomes…" found that the Centers are more diverse than the departments from which researchers were drawn.

Leaders must show a commitment to diversity. Leaders can influence who participates in review panels, who serves as roles models for students, and who is recruited to graduate programs and to new faculty positions. For example, leaders can counter the tendency for departments to narrow their searches too quickly, which may exclude candidates who are unfamiliar or unconventional.

The rise of new technologically mediated social networks offers a new opportunity to enhance diversity. These networks typically are much more extensive than geographically or institutionally oriented networks. The directors of interdisciplinary programs can draw on these networks not only for recruits, but also for mentors and advisers.

***"Diversity is not just names on a roster. What makes a group go is having a certain kind of social sense where it takes the most and best that all of its members can produce."* -- Ed Hackett**

***"Mixed groups, whether we're talking about culture or science, have a higher potential for conflict. But that higher potential for conflict is also a resource for the group to work with."* -- Howard Gadlin**

***"Interdisciplinarity denotes intellectual diversity and its integration, and that means the people who are produced from those efforts. So for me the focus is one of composition: who's participating in review panels; who's serving as faculty role models; and who's being recruited to graduate programs and to the faculty?"* -- Daryl Chubin**

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Processes for Creating an Interdisciplinary Program

A clear vision, goals, and strategy are essential for interdisciplinary research. This requires establishing broad research directions and specific research plans. Not all ideas are suited to interdisciplinary research. Drawing on his own experience as a former Director of the National Institute of Mental Health, Alan Leshner mentioned early efforts to pursue the genetics of mental illnesses. In those days, understanding of mental illness and the genetics of complex disorders had not progressed to the point where interdisciplinary research could be productive.

Several innovative methods have been developed to identify topics amenable to interdisciplinary research. One is to combine disciplinary understanding of individual networks into a multilayered knowledge network that would reveal the connections between knowledge domains. For example, this approach could be applied to the range of disciplines extending from basic biological research to clinical medicine. Self-assembling multidisciplinary teams could form in areas where layers of understanding connect and interdisciplinary approaches are pursued.

Another method, known as the sandpit, brings together researchers from different disciplines for an intensive multiday brainstorming session designed to generate potentially transformative interdisciplinary research topics. For example, the Engineering and Physical Sciences Research Council of Great Britain has used this method to distribute millions of dollars of research funding to interdisciplinary teams of researchers for projects developed during sandpit sessions.

Defining the Mission

A clear mission statement is particularly important for long-term interdisciplinary programs. These mission statements should meet several criteria:

- They should stand the test of time, because people will continue to refer to them for guidance.
- They should provide core values and clear direction for future leaders and participants in a project.
- They have to be plausible and understandable. Brevity is a virtue, as is a connection to the broader mission of an institution.

At the symposium, Barbara Wold, Director of the Beckman Institute at the California Institute of Technology, offered the Institute’s mission statement as an example:

> The mission of the Beckman Institute is to invent methods, instrumentation and materials that will open new avenues for fundamental research in the chemical and biological sciences, and to provide technological support for these efforts. The Beckman Institute strives to provide the kind of environment and support that will foster the initiation and early development of research thrusts too innovative or too "high-risk" for the regular sources of research support in government and industry. Activities within the Beckman Institute will be characterized by their promise of significant technological advances in

> fundamental fields of biology, chemistry and related sciences. The new knowledge that results will ultimately lead to great practical benefits for society and mankind. The Beckman Institute will also further the educational mission of Caltech by actively involving students in its activities.

Contrasting statements within a mission statement can create a productive tension, according to Wold. For example, does every project need to fulfill the mission of the Beckman Institute, or should some projects be focused on part of the mission and some on other parts? What is the proper balance between fundamental research and technology development?

The Beckman Institute has adopted a portfolio approach in which a combination of projects achieves the institute's mission, but other approaches are possible. In addition, change is expected at the institute and is encouraged through pilot projects, the involvement of external advisors, and recruitment of young faculty. Nevertheless, a mission statement should continue to apply even in the midst of change.

Adopting a new mission may require revolutionary rather than incremental change. A major challenge then becomes how to move an institution and individuals from one peak of performance to another without becoming mired in a trough between peaks. Adherence to underlying values can guide a transition in which research goals change but a commitment to excellence does not.

Governance

The composition and attitudes of the committees charged with creating and managing interdisciplinary programs or developing interdisciplinary incentives or review processes are critical. Keith Yamamoto, Vice Chancellor for Research at the University of California San Francisco, suggested inviting members from different disciplines and career stages who are committed to a vision of an institution's culture and to the need for interdisciplinary research. Senior-level and highly respected people are important for visibility, impact, and persuasion of key individuals at the institution. These committees also should include early-career faculty members who are pursuing interdisciplinary approaches. Yamamoto recommended recruiting these members faculty just after tenure, so that committee service does not complicate the already challenging process of tenure for interdisciplinary scholars.

Embedding a Program Within an Institution

Different types of research institutions have advantages and disadvantages for interdisciplinary research. Large research institutions can have a diversity of expertise, research infrastructure, and formal interdisciplinary programs. As a result, the right combination of collaborators may exist within a single institution. However, a critical mass of researchers in one's own field may decrease the likelihood of venturing outside of one's own area. Similarly, labs that can afford to buy their own research equipment are less likely to seek collaborations. At smaller colleges, where there may not be a critical mass in any discipline, many faculty members are accustomed to interacting with colleagues in different fields. Furthermore, limited research infrastructure in small institutions often compels faculty to forge partnerships both within their own institution and across institutions to leverage scarce resources.

Non-research colleges and universities can have a very difficult time accessing interdisciplinary research. Community colleges and resource-limited institutions are particularly at risk, and yet half of all undergraduates have taken some courses in community colleges. This proportion is even higher for minority students. If community colleges cannot train competent and competitive future researchers, a significant group of students - particularly minority students - will be lost from the pool. Special attention needs to be devoted to these institutions to keep them from being at a severe disadvantage as interdisciplinary research becomes more common.

Rewarding Interdisciplinary Approaches

The reward systems in universities often do not recognize and reward interdisciplinary collaboration. Early-career investigators in particular often face difficult decisions when becoming involved in interdisciplinary research. Even if the investigator is interested in interdisciplinary approaches and the institution promotes interdisciplinary work, the need to earn tenure in a disciplinary area often requires delaying interdisciplinary work until after tenure.

One way to reduce the risks for young investigators who engage in interdisciplinary work is through explicit agreements about responsibilities and rewards both to one's department and to the interdisciplinary project or institute. On a team level, these agreements might cover overall goals, work plan and timeline, authorship and credit, contingencies, communication practices, potential conflicts of interest, and resolving disagreements. Such agreements can help an interdisciplinary team articulate a shared vision and build trust. On a department or institute level, such agreements could be part of offer letters to new faculty, and spell out review criteria and reward procedures and describe mentoring arrangements for tenure track investigators. They could describe expectations for joint appointments and how to make changes in agreements.

Salaries, whether paid through a department, through an interdisciplinary program, or through some combination of the two, can be structured to support interdisciplinary research. Flexibility is essential to meet the needs of individual researchers and students and to make changes as an interdisciplinary program evolves.

The allocation of indirect costs requires negotiation and planning. One possible solution is to let indirect costs flow back to a home department in return for strong support from the institution for an interdisciplinary center.

Collaborative Space

The physical location of interdisciplinary research can be an important factor in its success. Researchers can work in a departmental building, in a building designated for interdisciplinary research, or off-campus. Space can be set aside for visiting collaborators, or they can be accommodated within existing space. Core facilities can be located within a building designed to attract interdisciplinary researchers for short periods to conduct specific tasks.

Each arrangement has advantages and disadvantages. (The four sidebars to this chapter demonstrate part of the range of possible arrangements.) Separate buildings can help foster an interdisciplinary program, but they also can separate research from other activities on campus. Incidental interactions, such as eating lunch or riding in the elevator, can make a big difference in research, and increasingly sophisticated electronic communications can make it easier for distant researchers to collaborate. People within an institution can occupy space set aside for visiting collaborators if it is desirable, or it can be left vacant for long periods. A building containing core facilities can come to be seen as a place to carry out tasks, not as a center for intellectual discourse and innovation. Different models will be appropriate for different institutions and different problems.

Transitions can be especially challenging. When people are asked to join an interdisciplinary team by moving into a separate building, it sometimes can be difficult to relocate them if the project ends or their research moves in a different direction from the rest of the team. One option is to allocate space for a set period with review and possible renewal at the end of that period. Home departments need to be ready to take researchers back if a move does not work out or if an interdisciplinary program changes direction.

"The integration of interdisciplinary ideas is a process. It leads to products, just as we often talk about fire as a thing, as a product. But fire, remember, is combustion. It's a process. And what we want to move toward is understanding the process in ways that allow us to think about it more productively." **-- Ed Hackett**

"We have to make systematic adjustments in institutional structures of rewards, in funding agency structures, in review procedures, and in committees and panels." **-- Alan Leshner**

California Institute of Technology: The Beckman Institute

The Beckman Institute at the California Institute of Technology has the fundamental mission of doing great research and creating the next generation of great researchers. But even this straightforward mission, in the context of interdisciplinary research, can raise questions. Should research at an institute evolve over time by changing people or changing projects? How much space and funding should be set aside for revolving door activities? To what extent should the institute pursue technology development as opposed to basic research?

The Beckman Institute has answered these questions in ways that reflect its mission and circumstances. To ensure continual change in both people and projects, the institute invests funds in pilot projects proposed by faculty members. Members of the Institute use jointly developed criteria to make funding decisions. Advisors from inside and outside the Institute shape the strategy and act as emissaries to the rest of the university.

The Institute does not appoint faculty. The approximately 35 biology faculty and 55 chemistry faculty are from disciplinary departments at Caltech, which retain the power of recruiting, appointment, and tenure. People who work in the institute's building can be asked to return to their departments. Though most of the space is reserved for long-term faculty, some is set aside for short-term projects.

Finally, the Institute created resource centers that have tripartite missions: carry out cutting-edge research; advance research capabilities by means of the invention and development of new methods, instrumentation, and materials; and establish, maintain, and operate a user-friendly facility relevant and available to a broad cross-section of the research community, particularly at Caltech.

For more information: http://www.its.caltech.edu/~bi

Georgia Institute of Technology: Interdisciplinary Research

In the 1980s the Georgia Institute of Technology recognized the importance of the biological revolution, which led to the creation of the Parker H. Petit Institute for Bioengineering and Bioscience (IBB). Faculty moved into the new IBB building on campus in 1999, at which point the interdisciplinary program became the heart of the biosciences community at Georgia Tech. Today, the biotechnology complex encompasses new buildings specializing in environmental science and technology (2002), biomedical engineering (2003), material and molecular science and engineering (2006), and nanotechnology (2007).

The IBB recruits faculty by working with participating academic units, because the positions ultimately reside in those units. Faculty members work together in the same buildings, which were designed to provide an environment conducive to interdisciplinary research. The IBB building has a central atrium, core facilities, a vivarium for animal research, a café to promote interaction, monthly social events to build community, and a seed grant program that provides funding for projects sponsored by at least two co-PIs from different colleges.

Faculty offices are together and not with their laboratories so that faculty interact with each other and work together. Laboratories are largely open, encouraging graduate students and postdoctoral fellows to interact. At the same time, the open laboratory space is not too large, which can reduce productive interactions. Many faculty members have less laboratory space in the IBB building than they did in their original locations, but the shared space has compensated for lost space.

The physical and organizational structure of the Institute for Bioengineering and Bioscience is designed to maximize opportunities for chance meetings. Such meetings are among the intangible benefits of interdisciplinary research that are very important but difficult to measure. A simple conversation can lead a researcher to look at a problem in a new light or foster a partnership that would not have occurred otherwise. Faculty also are attracted to Georgia Tech by its interdisciplinary environment, which has created communities of researchers who easily self-assemble into productive teams.

"Research is a people business. We have to keep that in mind as we move forward." **-- Robert Nerem**

For more information: http://www.ibb.gatech.edu

Stanford University: The Bio-X Program

The Bio-X Program at Stanford University supports, organizes, and facilitates interdisciplinary research connected to biology and medicine. It brings ideas and methods from engineering, computer science, physics, chemistry, and other fields to bear on important challenges in bioscience, creating new collaborative teams, significant biomedical discoveries, and new opportunities in fields outside biology. Bio-X includes 44 faculty located in the James H. Clark Center on campus, and more than 400 faculty from across the university.

A major feature of Bio-X is the Interdisciplinary Initiatives Program, which provides seed funding to faculty for high-risk interdisciplinary research projects that have the potential to transform knowledge. About $3 million is made available in competitions that have been held every two years for the past decade. Projects receive about $150,000, or $75,000 per year, which can support the human or technological resources needed to pursue an interdisciplinary project. In 2010, 227 faculty members from 51 departments and 5 schools across Stanford applied in teams, with about 20 awards granted. Between 2000 and 2010, $12 million was invested through the program, with about 100 projects being funded. That $12 million in internal grant support helped create more than $140 million in external grant support, representing more than a tenfold return on investment.

An ongoing study of Bio-X has demonstrated a large proliferation of interactions among faculty members as a result of the program. The program has resulted in hundreds of publications, more than 30 patents, and 6 start-ups. In addition, graduate fellowships train students to work at the intersection of disciplines, and undergraduate summer fellowships provide experiences in interdisciplinary research. The program has created a new, horizontal structure across the university, helping to break down silos between disciplines and creating a new model for research universities.

The founding faculty members of Bio-X were chosen for their entrepreneurial spirit and proven record of collaboration. Faculty propose research ideas rather than having research themes imposed through a top-down process. The program requires strong departments, which continue to hire and promote participating faculty. Bio-X seeks to empower faculty, which means that it has to maintain good relationships with departments. Programs funds do not come from departments but represent new funding. Through this approach, Bio-X has created substantial intellectual capital -- new knowledge at the intersection of fields, new technology, and new training opportunities for students.

"Bio-X is a university wide web of faculty whose collaborative research and teaching focus on the complexity of the human body in health and disease." **-- Carla Shatz**

For more information: http://biox.stanford.edu

University of California Berkeley: Reorganization of the Life Sciences

In 1981 the University of California, Berkeley, initiated a process that led to the realignment of fourteen biology departments into two. Dan Koshland, who was able to secure funding from the state of California to build two new buildings, led the process. Just as important was the formation of the Chancellor's Advisory Council on Biology (CACB), which is made up of top faculty members and reports directly to the chancellor and vice chancellor. This administrative structure created the bottom-up and top-down support essential to interdisciplinary research.

The CACB ensured that faculty search committees were interdisciplinary. It greatly expanded the range of disciplines represented by newly hired faculty and fostered cross-departmental programs and interactions. It also established the Health Sciences Initiative to help fund interdisciplinary centers.

Today the Health Sciences Initiative remains a highly cooperative and integrated initiative involving about 600 faculty and 14 departments from throughout the sciences. It has resulted in the establishment of multiple interdisciplinary centers focused on topics from stem cell research to energy to synthetic biology to neglected diseases. It also has resulted in the creation of many new undergraduate and graduate courses.

Initially, the greatest supporters of the initiative were early career faculty, who saw enhanced opportunities in an interdisciplinary program. Today, faculty members at later stages of their careers are equally strong supporters because of the increased quality and funding opportunities the program has created.

The initiative continues to face challenges of funding and politics. The solution to this difficult has been to retain flexibility so that continued re-alignments are possible. Growth and restructuring also have helped avoid stagnation. Taking the lead from young faculty helps ensure that the academic structure keeps changing.

"Each institution will have its own challenges because institutions have a different mix of people and emphases, but it can be done." **-- Robert Tjian**

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Interdisciplinary Education

People with interdisciplinary training will be in great demand in the future. The complex problems of the 21st century demand graduates who can integrate knowledge from many disciplines and domains. Future researchers will need to understand jargon, approaches, and standards of proof across fields. Colleges and universities will need to figure out how to provide students with this training despite their largely disciplinary structure.

Undergraduate Education

Interdisciplinary approaches have the potential to transform education in science, technology, engineering, and mathematics (STEM) at all levels. Today, the vast majority of precollege and higher education occurs within a disciplinary framework, yet this educational framework is not producing optimal outcomes. As David Botstein of Princeton University pointed out, more than half of the students who enter college intending to major in an area of science or engineering switch to a non-STEM major during their first two years of higher education, and attrition rates are disproportionately high for minority students.

Introductory courses in science and engineering can be a significant hurdle for many students regardless of their level of preparation. Most of these courses are taught in more or less the same way they were taught a half a century ago. Very few discuss current challenges and research frontiers. The number of pre-medical students in these courses tends to be high, and these students can view introductory courses as necessary evils en route to their goals. Many senior-level professors shun these courses, and classes tend to be large and impersonal. While some students inevitably discover new interests in college and move away from science and engineering, others are driven away and leave these fields with a sour view of the subjects.

Interdisciplinary approaches can help students retain interest in science and engineering, particularly if they are offered throughout the college experience, not just after fulfilling a number of disciplinary requirements. Instead of creating education programs around “everything one needs to know in X discipline,” interdisciplinary education can base courses on large and compelling problems. This allows professors to introduce relevant disciplinary concepts in a “just in time” fashion. Students stay engaged and learn to integrate approaches from different disciplines to solve problems.

Graduate Education

Graduate education will inevitably become more interdisciplinary as interdisciplinary research becomes more common, but graduate students will still need depth of expertise. The most likely prospect is that most graduate students will continue to develop deep expertise within a discipline. At the same time, more and more students will develop a broad literacy across scientific endeavors. They will be familiar with the broad concepts and techniques in different disciplines and will be able to communicate with people in those disciplines. They will be parts of networks of people that span disciplines.

Interdisciplinary training at the graduate level will require new ways of evaluating the contributions and achievements of students, but these challenges are not insurmountable. High energy physics, for example, has found ways to identify the contributions of individual students and young investigators in the context of team work.

Interdisciplinary approaches in advanced education already are becoming much more common. Since 2001, the number of respondents to the National Science Foundation's Survey of Earned Doctorates who report working in two or more research fields for their dissertation has fluctuated between 24 percent and 30 percent. From 2004 through 2008, more than 40 percent of Ph.D. recipients from MIT reported working in two or more research fields. One source of support for the development of such programs is the National Science Foundation's Integrative Education and Research Training (IGERT) program, established to support the development of "new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries."

"Students are changing. They're changing demographically, and they're changing in terms of what they bring to the classroom and how they are ready to learn." **-- Peter Bruns**

Princeton University: The Integrated Science Program

The Integrated Science program at Princeton University is an interdisciplinary science curriculum for first- and second-year students considering a career in science. Students are recruited for the program from the day they are admitted to Princeton because they have to start it at the beginning of their freshman year. The curriculum covers in an integrated manner the core material of introductory physics, chemistry, biology, and computer science. Mathematics, computational methods, and quantitative problem solving are emphasized throughout the program.

The course has a maximum enrollment of 64 students and is taught by top faculty at Princeton, who engaged in lengthy negotiations to decide the structure and content of the curriculum. Generally, students read key papers that reflect the current state of scientific subjects without lingering on the history of discoveries in every field. All of the sciences are taught at a level that satisfies the departmental requirements for introductory courses.

In the first year, students take a double credit course that includes five hours of lectures, three hours of laboratories, and a three-hour computational precept. In the second year, students take a single course that meets for three hours a week. In their junior and senior years, students are free to major in any discipline they choose. Most students consider Integrated Science the hardest course that can be taken at Princeton.

***"We threw away the traditional and stuck with the fundamental, and then we added the things that we thought were missing, mainly computer science and statistics."* -- David Botstein**

For more information: http://www.princeton.edu/integratedscience

Yale University: Interdisciplinary Team Teaching

Institutions have many possible ways to immerse students in interdisciplinary education. One approach described at the symposium by Jo Handelsman, professor of molecular, cellular, and developmental biology at Yale University, involves forming teams of graduate students drawn from different disciplines. These students receive training in the teaching techniques, such as active learning and inquiry-based instruction that have been demonstrated by education research to improve student learning. These teams then develop and teach a unit of material that can be taught within a particular course. Comparison of the units permits successful ones to be replicated, both within a single institution and, via the web, in multiple institutions.

Such an approach benefits both the graduate students who develop and teach the unit and the undergraduates who learn from it. Teaching requires learning new concepts, collaborating with others, and encouraging other people to engage with information. The graduate students who teach the units find common ground across their own disciplines and learn to speak in the language of another discipline. They hone their pedagogical knowledge and create a product that can be widely disseminated. Graduate students emerge from the experience with skills that would increase their attractiveness as researchers and instructors.

The University of Colorado Boulder: Interdisciplinary Graduate Education in Quantitative Biology

The goal of the Interdisciplinary Quantitative (IQ) Biology program at the University of Colorado, Boulder, is to attract, engage, and empower collaborative graduate students who want to use interdisciplinary approaches to tackle bioscience questions. IQ Biology applicants are considered simultaneously by several participating Ph.D. degree programs and the IQ Biology certificate program. IQ Biology has 35 core faculty from eleven departments and six focus areas: mathematical biology, computational biology, bioengineering, biophysics, image analysis, and chemical biology.

In their first year, students take interdisciplinary, project-based courses and conduct research independent from a specific department. They are initially independent from a specific department; at the end of the first year they choose a Ph.D. degree program. In their second year they do research in quantitative biology while gaining disciplinary depth in their chosen Ph.D. degree program. In their third year they continue their research using their disciplinary expertise and interdisciplinary dexterity. Graduates receive a certificate in IQ Biology and a Ph.D. from one of the following degree programs:

- Applied Mathematics

- Biochemistry
- Chemical and Biological Engineering
- Chemical Physics
- Computer Science
- Ecology and Evolutionary Biology
- Mechanical Engineering
- Molecular, Cellular, and Developmental Biology

Setting up the program required signing memoranda of understanding with individual degree programs to delay departmental courses and exams until the second year and to count nine credits of first-year courses toward the Ph.D. degree. Measures of success, in addition to increased numbers of collaborative papers, include having professors from other departments on thesis committees and students who consider postdoctoral research in departments representing different disciplines than the ones from which they received their doctoral degrees.

***"Quantitative tools are the limiting factor to advancement in the biosciences, especially now that we have this enormous amount of information."* -- Tom Cech**

For more information: http://iqbiology.colorado.edu

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Supporting and Sustaining Interdisciplinary Research

Interdisciplinary research can be difficult to support and sustain for a variety of reasons. Existing funding mechanisms are generally aligned with disciplinary research. When institutions are financially strapped, they have a tendency to protect "core" activities, including disciplinary research, creating dramatic fluctuations in support for interdisciplinary research. Interdisciplinary research sometimes begins as a pilot project, which can require a transition from exploratory awards to much larger funding commitments. Governmental support also can fluctuate as policies or politics change.

Supporting Interdisciplinary Research

Federal funding mechanisms are not necessarily well suited for interdisciplinary research. Interdisciplinary research can be risky, and federal funding agencies tend to be risk averse. Federal funding is often targeted toward individual projects rather than group projects, and award sizes are often modest and for a short period of time. Also, the peer review process can have trouble evaluating projects that cross disciplinary or programmatic boundaries.

Because interdisciplinary research is often oriented around problems that are broader than those tackled by individual disciplines, it can attract funding from many other sources. State funding agencies, for-profit companies, venture capitalists, and philanthropies can all be motivated to invest in interdisciplinary research. In some cases, prizes may play a role in creating incentives for groups to arrive at interdisciplinary solutions to a problem.

An alternate approach for public or private funders is to support individuals who can build interdisciplinary teams. The Howard Hughes Medical Institute makes long-term bets on people rather than projects, including promising early-career investigators. Unfettered funding with periodic review and renewal of support allows investigators to pursue risky or interdisciplinary approaches.

In many cases, the private sector is in a stronger position to fund interdisciplinary research, both because it is more accustomed to taking risks and because it sees the commercial value of some interdisciplinary research. A potential drawback to private funding is that it can be so focused on applications that it detracts from the educational and research missions of institutions.

In some cases, existing funding can be leveraged to support interdisciplinary research in a way that does not require large additional expenditures. For example, interdisciplinary research can be structured as a self-sustaining, horizontal network of collaborations across existing disciplines or departments. In this way, interdisciplinary ideas and funding can bubble up from faculty members and be layered upon disciplinary efforts.

Sustaining Interdisciplinary Research

Given the complexity of many interdisciplinary problems and the difficulty of coordinating collaborative projects, interdisciplinary research can take a long time. Given that the current research funding system generally supports projects for a few years, how can it support interdisciplinary projects that may require a decade or more to succeed?

Multiple sources of funding can help to sustain interdisciplinary research. Interim goals or periodic review can ensure that such research is moving forward. Some level of institutional or private funding may be needed to help interdisciplinary projects get through the academic equivalent of the "valley of death" in the commercialization of research results.

Sustainability does not mean stagnancy. Programs, people, and funding sources necessarily change over time. However, a portfolio of projects within an institution can be relatively stable, even if a single program is not.

The Research Corporation: Funding Research at the Borders of Disciplines

The Research Corporation for Science Advancement, which was founded in 1912, is the oldest foundation in the United States dedicated solely to the funding of science. Its goal is to transform science in the 21st century through innovative high-risk research and new forms of partnerships. It engages in what it calls venture philanthropy, or philanthrocapitalism, which takes concepts and techniques from venture capital finance and high-technology business management and applies them to achieving philanthropic goals.

An approach the corporation has pioneered is known as *Scialog*®, which is a portmanteau of 'science' and 'dialogue.' Its objectives are to provide funding for early-career scientists who have recently received tenure, since this is when many scientists are able to undertake highly original and creative research. It supports high-risk, high-reward research that might fall outside the boundaries of traditional funding streams by convening interdisciplinary teams of researchers focused on broad problems of importance to society. In 2010, for example, a ten-person review panel funded 13 of 78 solar energy-related proposals at up to $250,000 each.

During the 2010 Scialog conference held at Biosphere 2 in Arizona, the successful teams competed for supplemental challenge grants of $100,000 each, and three catalytic grants were awarded. A post-conference survey of participants showed that a majority very much agreed that Scialog is a viable approach to accelerate high-risk, high-reward research.

"If you explore, listen, learn, brainstorm, design, innovation, and reach out to bring partners in, you can get collaboration to occur." **-- James Gentile**

For more information: http://rescorp.org

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Measuring the Outcomes of Interdisciplinary Research

Interdisciplinary research seeks a synthesis of data, concepts, and methods to extend the scale, scope, and range of an explanation or action. It is more than just bringing people together. It is innovative, creative, and potentially transformative.

Theories of Interdisciplinary Research

Ed Hackett, professor of sociology at Arizona State University, proposed a theoretical framework for the evaluation of interdisciplinary research consisting of four factors:

- *Intellectual, social, and technological capital:* Resources that can be brought to interdisciplinary research include the ability, preparation, and knowledge of the people involved in the synthesis, along with the extent and richness of their networks both within and outside an institution. Capital also includes the ensemble of research technologies that investigators can apply to a problem.

- *Diversity in person and agreement on process:* Interdisciplinary groups excel when a diverse set of people have a collective sense of how they can work most effectively. Merely having people present on a roster will not work if they do not contribute to this sense of cohesion and purpose within a diverse context.

- *Intensity and focus:* Intensity includes emotional energy, which is essential for diverse and skilled people to work together.

- *Duration:* Intensity needs to be sustained for interdisciplinary research to overcome barriers and make progress on difficult problems.

This framework can be used to look at whether a program is well-conceived and being executed properly. At the same time, the most important measure of interdisciplinary research is whether it solves the problems it set out to solve.

Traditional and Innovative Metrics

Many traditional metrics can be applied to interdisciplinary research as well as to disciplinary research. Grants secured, papers published, patents received, companies started, and students graduated all can be used to assess interdisciplinary programs and projects. Visiting committees can study and report on the progress of interdisciplinary efforts.

In addition, it may be possible to measure the degree of synthesis achieved through an interdisciplinary project through a careful reading of papers or examination of processes within the project. Social networks within groups and between groups can measure the degree of interconnectedness among disciplines. Instead of being judged by such measures as the publication of papers in prominent journals, some researchers may be judged in part by their contributions to large teams, curated databases, or data dissemination.

Institutions may wish to evaluate the effectiveness of their interdisciplinary policies. To do so, they may look at a number of metrics:

- How many collaborators does a person have?
- What are their fields?
- What fraction of a person's publications is collaborative?
- How many new collaborations have been established over the past five years?

An even more innovative approach could incorporate video recordings of group interactions or metering with sociometric sensors. These could be used to measure episodes of speech (including duration, timing, interruption, overlap, volume, and pitch); movement (including timing and duration); and the orientation of individuals to one another within and outside meetings. Such measures can reveal patterns of communication by gender, seniority, discipline, or ethnicity as well as the engagement, emotional energy, and the social structure of a group.

***"Much of what goes on in universities and colleges involves individuals who are very sophisticated and very highly trained. The challenge is going to be, how do you innovate in the midst of excellence?"* – James Collins**

***"Universities and science are both conservative entities, yet we're trying to reach for something that's very different. Ultimately, it is the creativity of the community that leads to innovation."* -- Jo Handelsman**

NSF Science and Technology Centers: Measuring the Success of Interdisciplinary Centers

Between 2000 and 2009, the National Science Foundation (NSF) funded 17 Science and Technology Centers (STCs), which conduct interdisciplinary, collaborative, inter-institutional research directed at complex, high-priority, science-based questions. In 2011, a multidisciplinary AAAS team released an assessment of the STC program in five areas: research, education, diversity, knowledge transfer, and integrative partnerships.

In *research*, the team found that the STCs are adding value to the research portfolio supported by NSF in several ways. Individual centers are changing the scale of analysis or synthesizing across scales, improving instrumentation, generating new scientific and technological knowledge relevant to important societal issues, generating new platform technologies and materials that can contribute to many different fields, and exemplifying a new paradigm in science based on the use of digital technologies to generate new data sets and test scientific hypotheses. Faculty members participating in the centers were more likely to publish in a broader array of peer-reviewed journals, and they had an increased appreciation of and willingness to collaborate with faculty from different disciplines.

In *education*, the STCs have a stellar record of renewing the science and engineering workforce. Half of the STC alumni responding to a 2010 survey hold faculty positions, and another third are in postdoctoral positions. The STCs are also systematically engaged in programs at K-12 institutions, community colleges, and institutions conducting informal science education, which is not routine for academic research centers.

In the area of *diversity*, STC participants are more diverse by gender, race, and ethnicity than are the departments from which they were recruited. The representation of students of color and women is greatest at the undergraduate level and better than the national average at the graduate and faculty levels.

With regard to *knowledge transfer*, more than 40 percent of participating faculty respondents participated in the knowledge transfer or product development activities of their centers. More than one in three respondents indicated that their participation in the center had led to more interaction with industry as compared with other members of their department. Of student respondents, 80 percent felt that allowing their participation in knowledge transfer activities had been a net benefit.

Finally, each of the 17 STCs engaged in numerous *partnerships* with a diverse, albeit at times changing, set of partners. Furthermore, these were formal partnership involving resource commitments between the host institution and the partners.

"Diversity should be at the center of what Science and Technology Centers do. It should not be on the margin or an add-on but rather should contribute to the synergies of what goes on inside a center." **-- Daryl Chubin**

For more information: www.aaascapacity.org.

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Closing Thoughts

Interdisciplinary research can have many benefits for an institution and for the people who work and study within that institution. While there are many challenges to creating and sustaining programs, symposium participants were unanimous in their belief that research in the 21st century requires interdisciplinary approaches. The symposium closed with brief statements from all participants that summarized what they thought were the most important lessons from the one-and-a-half day event. Excerpts from some of these statements are below.

"We all agree that interdisciplinary efforts in both research and teaching are important. But the local environment is just as important in defining how we're going to deal with interdisciplinary approaches as the general environment." **– Robert Tjian**

"Interdisciplinary research is all about change, and it's about people being able to change. And the easiest place to change people is when they're early in their thinking, so listen to the young." **– Robert Tjian**

"We need to make these system-scale changes experimentally, knowingly, and adaptively, which means we have to treat interdisciplinary research as a grand experiment in transforming a society's knowledge system, the system that produces, shapes, and uses knowledge." **– Ed Hackett**

"One of the great victories of biomedical research has been that our field has moved from being descriptive to quantitative. As a result, the gaps between data and knowledge and knowledge and understanding have actually increased. That obligates us to become multidisciplinary in order to move forward. We must have the courage to make a decision that this is what we're going to do. One of the most encouraging things about this meeting is that we're hearing about models that can be successful in different ways and in different venues. The challenge will be to keep communicating with each other to establish what those best practices may be." **– Keith Yamamoto**

"As we go forward, we need to find ways to move the funders toward the support of interdisciplinary research without creating a big, expensive infrastructure that becomes very complex and threatens other modes of supporting research." **– Alan Leshner**

"The model that you use will depend on local campus politics, but more than one model can work." **– Robert Nerem**

"We should be giving our Ph.D. students much more control of their destiny and education. They have a passion, and we ought to create programs that allow them to follow their passion". **– Robert Nerem**

"You have lots of information and lots of challenges coming at you from both outside and inside the institution. Unless you're very clear-headed about the value system that's motivating you, you can get off course very quickly. Values must be central to what you're doing." **– James Collins**

"People and institutions need to be fearless to be interdisciplinary -- but not cavalier. You need to be fearless - especially the old folks - about being willing to trade away some things you might have held dear to get the good things that go with being interdisciplinary." **– Barbara Wold**

***"As we move forward, we're going to come up with a number of different models, taking pieces and bits that work and putting them together. Then, in the future, we'll be able to do interdisciplinary research seamlessly because it will become part of what an institution does."* – Michelle Bennett**

***"I am struck by what I perceive to be convergent evolution, because a lot of us are creating programs with many similarities."* – Leslie Leinwand**

***"The strengths of the university structure itself, including departmental structures, are essential for building additional programs and horizontal networks on top of those structures."* – Carla Shatz**

***"A lot of challenges are left. A big one is how to continue to fund this process. How can it become, I don't want to say institutionalized, but secured so that the evolution can continue."* – Carla Shatz**

***"When I used to play high school football, I was a pulling guard, and a pulling guard is a big, slow guy who pulled out of his position after the snap, found and hit the biggest guy across the line, and let the halfbacks, who were deft at what they do, score. This is what a good academic leader should do -- pave the way for young faculty. Those younger faculty and the students they're teaching are the talent that will make the breakthroughs that matter."* – Jim Gentile**

***"The good news is that there is so much that is agreed upon about what the task is. The bad news is that I don't think anybody, with very few exceptions, is making any headway against the established departments and hierarchies."* – David Botstein**

***"At the end of the day there's still too little emphasis on the education piece. I don't believe that my generation or the generation immediately after is ever going to become interdisciplinary in any meaningful sense. It is today's students who will be the first real interdisciplinary generation."* – David Botstein**