BPA News

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Assessment of the Office of Fusion Energy Sciences Released

Charles Kennel, Director, Scripps Institution of Oceanography, and Chair, Fusion Science Assessment Committee

I recently chaired a committee that was charged to carry out an assessment of the scientific research program of the Department of Energy's Office of Fusion Energy Sciences (OFES). The report, which was requested by the Director of the DOE's Office of Science, was released on October 23 at a meeting of the American Physical Society's Division of Plasma Physics. This article is based on the report. A link to the full text of the report may be found on the committee's Web page at http://www.nas.edu/bpa/projects/fusac/.

An important aspect of the context for this study is the cancellation of U.S. participation in the ITER project, which was an international collaboration to build a large tokamak fusion reactor. Subsequently, the 1996 appropriations bill for DOE specified a change in the mission of the fusion effort, which was directed to restructure itself as a science program. Up to that point, the goal was primarily to develop fusion as an energy technology.

The purpose of the report is to evaluate the quality of the OFES research program and to provide guidance for the future program strategy aimed at strengthening the research component of the program. The committee restricted its review of the fusion program to magnetic confinement, or magnetic fusion energy (MFE), and did not address inertial fusion energy (IFE) in detail because MFE-relevant research constitutes roughly 95 percent of the funding in the Office of Science fusion program. Unless otherwise noted, any reference to fusion in this article should be assumed to refer to magnetic fusion.

Fusion research carried out in the United States under the sponsorship of OFES has made remarkable strides over the years and recently passed several important milestones. Significant progress has been made in understanding and controlling instabilities and turbulence in plasma fusion experiments, facilitating improved plasma confinement. Theory and modeling are now able to provide useful insight into instabilities and to guide experiments. Experiments and associated diagnostics are now able to extract enough information about the processes occurring in high-temperature plasmas to guide further developments in theory and modeling. Many of the major experimental and theoretical tools that have been developed are now converging to produce a qualitative change in the approach to scientific discovery in the program.

In the context of the international fusion energy effort, the U.S. program has traditionally played a central role as a source of innovation and discovery. The goal of understanding at a fundamental level the physical processes governing observed plasma behavior has been a distinguishing feature of the U.S. program. This role was formally recognized when the program was restructured in 1996. Over the past several decades, the United States has played a dominant role in plasma theory, which is an essential tool required to unravel the complexities of plasma dynamics. The quantitative detail in which experiments are designed and executed in the United States has become a benchmark for the rest of the world. However, close interaction between the U.S. and international programs since the

See "Fusion Science" on page 2

In this issue:

Physical and Life Sciences

William Bialek, NEC Research Institute

THE science session at the fall meeting of the BPA was devoted to the interface between the physical and biological sciences. Organized by David Galas (Keck Graduate Institute) from the Board on Biology and me, the session had several goals: to communicate the growing excitement about a diversity of topics where physics and biology intersect, to explain why the present time is a special one in the long history of interaction between the disciplines, and to catalyze discussion about where the field is going and how the boards can help.

Galas introduced the session, emphasizing the revolutionary transformation that has taken place in modern biology over the past decade. While biologists always have looked to the physical sciences for new instruments, the enormous quantities of data being generated in today's biology labs highlight the need for ideas and mathematical analyses as well as for measurement tools.

One of the major developments from the past decade is the ability to study the mechanics of single molecules. Physicists have contributed substantially, and traditional areas of physics have received some dividends. Some of the classic statistical mechanics problems in polymer physics are now best illustrated by experiments on individual biological molecules. George Oster (University of California at Berkeley) described the state of such experiments on the F0/F1 ATPase, the molecule responsible for synthesizing ATP in all our cells. ATP, in turn, serves as the universal

See "Physical and Life Sciences" on page 7

Fusion Science
(continued from page 1)

beginning of this field in the 1950s often makes it difficult to clearly separate contributions from the United States and the international program.

Mutual reinforcement of theory and experiment and significant international leadership are the hallmarks of a successful scientific enterprise. The committee concluded, therefore, that the quality of the science funded by the U.S. fusion research program in pursuit of a practical fusion power source (the fusion energy goal) is easily on a par with that of other leading areas of contemporary physical science.

In spite of the high quality of the science being carried out in the program, the committee noted some severe demographic and sociological problems, partly caused by programmatic emphasis and organizational structures. As outlined in the earlier interim report of the committee, there is a history of intellectual interchange between the fusion plasma community and the broader scientific community. Nevertheless, in recent years the increasing focus on the fusion energy goal has gradually caused the fusion program to be too inward looking. Research in the program has become intellectually isolated from the rest of science. Many of the scientific challenges that must be overcome in pursuit of the energy goal are sufficiently important to have broad impact on other branches of science. Most scientists funded by the program, however, do not actively participate in the wider scientific culture. As a result, the flow of scientific information both out of and into the field has stagnated. New ideas and techniques developed in allied fields are slow to percolate into the program. The high-quality science being done in the program is not widely appreciated outside the field, resulting in a generally negative view of fusion science by the broader scientific community. This isolation, combined with the generally negative perception of the field is narrowing the demographic base to a degree that endangers the future of the field of plasma science. The proportion of the program based on open competitively peer-reviewed grants is small, which discourages the entry of new talent into the field, further increasing the isolation.

The committee concluded that a dynamic, outward-looking, science-driven program, in which discoveries are regularly communicated beyond the walls of fusion science, is essential to alter the perception of the field by the outside science community. A strong case can be made that a program organized around critical science goals will also maximize the progress toward *a practical fusion power source*. Scientific discoveries that a decade ago would have been considered dreams are the fundamental drivers of program direction at all levels. Thus, scientific discovery is inherently coupled with progress toward fusion, and the two should not be considered opposing forces.

Primary Recommendations

The committee made the following seven primary recommendations to address the findings that raise concerns about the future of the fusion science effort:

(1) Increasing scientific understanding of fusion-relevant plasmas should become a central goal of the U.S. fusion energy program on a par with the goal of developing fusion energy technology. Decision making should reflect these dual and related goals.

The accomplishment of the scientific goals should serve as a metric for defining success within the program and should replace the previous emphasis on performance as the *only* measure of progress. Improvements in scientific understanding of fusion-relevant plasmas and progress towards fusion energy are coupled, and both should serve as measures of program success and be given comparable weight.

DOE, in full consultation with the scientific community, needs to define a limited set of important scientific goals for fusion energy science and formulate concrete and specific strategies to attack each issue.

Program planning and budgetary

See "Fusion Science" on page 4

Board on Physics and Astronomy Meets on West Coast

THE Board on Physics and Astronomy convened at the Beckman Center on the University of California at Irvine campus on November 4. The meeting opened with two project reviews.

The first item on the agenda was a summary of the recently released report *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program*. The chair of the authoring committee, Charles Kennel, Director of the Scripps Institution of Oceanography, made the presentation. He has summarized his remarks in an article that appears on page 1 of this issue of *BPA News*. The article is drawn from the executive summary of the report.

Kumar Patel then gave the Board a status report on the work of the Panel on the Future of AMO Science, which he chairs. This panel is preparing an update of the 1994 report *Atomic, Molecular, and Optical Science: An Investment in the Future*, which was the first volume of the new survey, *Physics in a New Era*. The panel has prepared an initial draft of its report and is reworking the material so that it will be accessible by a nontechnical readership.

Board meetings always feature a science session; the topic for this meeting was "The Connections Between the Physical and Life Sciences." Led by BPA member William Bialek and Board on Biology member David Galas, the session featured talks that ranged from biological machines at the molecular level to neurobiology. Dr. Bialek summarized the session in an article that begins on page 1 of this newsletter. The Board concluded that a workshop on the life-physical sciences connection should be designed in cooperation with the Board on Biology.

Michael Turner of the University of Chicago, chair of the Committee on Physics of the Universe, reported on the work of his committee. The CPU has completed a draft of the first phase of its report addressing the science priorities in the area where physics and astronomy intersect. The report will be entitled *Connecting Quarks and the Cosmos: 11 Scientific Questions for the Next Century*. In a second phase of the study, the committee will develop an implementation strategy.

Murray Gibson presented a proposal for a study of small facilities operations on behalf of the Solid State Sciences Committee. The study would consider the merits of consolidating assets into regional facilities that would have critical mass to successfully support and operate small facilities. The Board endorsed the study.

The policy session addressed the continuing problem of integrating the privately funded ground-based optical astronomy facilities in the United States with those that are publicly funded. The community has been struggling with the problem of providing instrumentation to the new privately funded telescopes that are coming on line so that optimal use is made of these facilities for advancing the science of astronomy. Alan Dressler, chair of the Panel on Ground-Based OIR Astronomy of the Survey of Astronomy and Astrophysics, made the presentation. The panel recommended that the National Science Foundation provide instrumentation funding for the private facilities in exchange for broad community access to the telescopes. The private facility directors have made a counterproposal, which is under consideration by the NSF.

A number of other committee chairs gave status reports on their activities. Among them were the chairs of the Astronomy and Astrophysics Survey Committee (AASC), the Physics Survey Overview Committee (PSOVC), the Committee on Astronomy and Astrophysics (CAA), the Plasma Science Committee (PLSC), and the Committee on Atomic, Molecular, and Optical Sciences (CAMOS). The AASC is completing the publication of its report, already released in prepublication form. The PSOVC report is in review. The CAA is planning to meet in December to consider a number of issues, including rescoping some of the priority missions recommended in the AASC report. The PLSC is launching a new study of high-energy-density plasma

See "BPA Meeting" on page 6

Committees of the Board on Physics and Astronomy

Committee on Astronomy and Astrophysics
John Huchra, Harvard-Smithsonian Center for Astrophysics, and Richard McCray, JILA/University of Colorado, Co-chairs

Committee on Atomic, Molecular, and Optical Sciences
Margaret Murnane, JILA/University of Colorado, Chair

Plasma Science Committee
Stephen C. Cowley, University of California at Los Angeles, Chair

Committee on Radio Frequencies
Paul Steffes, Georgia Institute of Technology, Chair

Solid State Sciences Committee
Sol Gruner, Cornell University, Chair

Astronomy and Astrophysics Survey Committee
Joseph H. Taylor, Princeton University, and Christopher F. McKee, University of California at Berkeley, Co-chairs

Fusion Science Assessment Committee
Charles Kennel, University of California at San Diego, Chair

Physics Survey Overview Committee
Thomas Appelquist, Yale University, Chair

Committee on Physics of the Universe
Michael Turner, University of Chicago, Chair

Committee for an Updated Assessment of Atomic, Molecular, and Optical Sciences
C. Kumar Patel, University of California at Los Angeles, Chair

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More information on BPA committees may be found on the BPA Web page at <www.national-academies.org/bpa>.

Fusion Science
(continued from page 2)

analysis carried out by DOE must be organized around answering key scientific questions in fusion-relevant plasmas, as well as around the progress towards the eventual energy goal. This requirement applies to the confinement configuration program element, as well as to other program elements of a more general nature.

Public and Congressional advocacy should emphasize progress in science as well as progress towards a practical fusion power source.

(2) A systematic effort to reduce the scientific isolation of the fusion research community from the rest of the scientific community is urgently needed.

Program planning, funding, and administration should encourage connectivity with the broad scientific community.

The community of fusion scientists should make a special effort to communicate their concepts, methods, tools and results to the wider world of science, which is largely unaware of recent scientific accomplishments. Increased connectivity will also facilitate the transfer of new ideas and techniques into the program from allied fields, enhancing the ability of the program to maximize the rate of scientific discovery.

There are numerous examples within federally funded research programs where formal coordination mechanisms have been established among common programs in different agencies. In some instances this coordination can yield more optimum use of funding. Perhaps of even more significance, the dialogue among the leaders of the related government programs encourages interactions among the various scientific communities, fosters joint undertakings, and raises the visibility of the discipline as a whole.

(3) The fusion science program should be broadened both in terms of its institutional base and its reach into the wider scientific community; the program should be open to evolution in terms of content and structure as it continues to strengthen its portfolio of research.

The committee is convinced that the opportunity to understand the plasma physics underlying fusion is expanding because of the closer connection between theory and experiment and through much improved diagnostics and numerical simulation. To enrich the pool of ideas to feed this accelerating progress, it will be essential to enlarge the sphere of awareness of the critical problems facing the field and to bring in new talent, both individual and institutional.

The problem of broadening the fusion science effort can be approached in a number of ways. One approach is to structure openly-competed-for funding opportunities of sufficient magnitude to elicit responses from potential new institutional participants in the field. The creation of centers of excellence in fusion science (proposed below) and an enhanced involvement of the National Science Foundation in fusion and plasma science would also broaden the institutional base of fusion science.

A larger proportion of fusion funding should be made available through open, well-advertised, competitive, peer-reviewed proposal solicitation. Fusion program peer review could involve scientists from outside the fusion community where appropriate. The evaluation and ranking of proposals by panels that include individuals with appropriate expertise from allied fields would broaden the intellectual reach of the grant review process.

Plasma science research that is not immediately related to the fusion energy goal should play a more influential role in the DOE fusion program. Inclusion of more plasma science in DOE's fusion science portfolio could be accomplished by a program element for "general plasma science." This program should award competitively peer-reviewed individual investigator grants. A small fraction of the present DOE program addresses this need, but its role and visibility should be increased. Such funding would encourage new interchanges that enrich fusion science.

To ensure that increasing institutional diversity is a continuing goal, the committee recommended that the breadth and flexibility of participation in the fusion energy science program be a program metric.

(4) Several new, openly competed centers devoted to exploring the frontiers of fusion science are needed for both scientific and institutional reasons.

Many of the issues in fusion science are now of sufficient complexity that they require closely interacting, critical-mass groups of scientists to make progress. For example, understanding the dynamics of plasma turbulence and transport requires the development of appropriate physical models and computational algorithms for treating disparate space- and timescales, as well as complex magnetic geometries, efficient programming on massively parallel computing platforms, and an understanding of nonlinear physics (energy cascades, intermittency, phase transitions, avalanches) and other topics.

No single scientist or even small collaborations of practicing scientists have the breadth of knowledge required to tackle such large and complex problems. The absence of critical-mass, closely interacting teams is inhibiting the successful attack on a number of central science issues confronting the fusion research program. The loose collaborations that have been periodically established by the program have generally not been successful in establishing the close working relationships required to address the most challenging topics.

New "frontier centers" could create a focus on scientific issues within the U.S. fusion program. Each center could either serve as a central node for a distributed network of close collaborators or undertake scientific explorations of significant magnitude at one site, or it could do both. These frontier centers could evolve into new, independent centers of excellence around the country, marrying the expertise and approaches of national labs and universities. The centers should have a number of programmatic and structural features so that they can play their appropriate role in addressing the critical problems of the field.

- A proposal for a center should have a plan to identify, pose, and answer scientific questions whose importance is widely recognized.
- One size cannot meet all scientific challenges. The committee envisions a

center comparable in size to current NSF-sponsored centers (with operating costs in the range of $1 million to $5 million per year), though the ultimate scale should be determined by the proposal process. Some centers may require on-site experimental facilities, and some may only require computing facilities and access to larger national computer centers.

- A team of around 4-6 coinvestigators with broad expertise and connections to other research groups and laboratories should form the core of the center's personnel. This team should be augmented by a similar number of temporary research staff (funded, at least in part, by the center) and an appropriate number of support staff.
- The center should enable links to various scientific disciplines, including physics, mathematics, computer science, and others, depending on the problem focus of the center. A proposed center program should have a plan to enlist new disciplinary and institutional participants to collaborate with the present fusion community and to make the experimental resources of the fusion community more widely available.
- The institutions housing or participating in such centers should make a commitment to add faculty or career staff, as appropriate, in plasma/fusion science or related areas.
- The centers should have a strong educational component featuring outreach to local high schools, a program of undergraduate research opportunities, and a graduate research program.
- Centers should sponsor multidisciplinary workshops and summer schools focused on their central problem that will bring together students and researchers from various fields and institutions. The objective of these workshops would be to bring in new ideas and collaborators as well as to disseminate understanding and applications to other fields of the results that are being achieved in the effort to address the fundamental problems of fusion science.

Examples of potential focus topics for centers include turbulence and transport, magnetic reconnection, energetic particle dynamics, and materials; others would emerge in a widely advertised proposal process. These topics are of broad scientific interest in allied fields. To build another bridge to related fields, the DOE should cooperate with NSF in establishing one or more centers addressing a topic of general interest in plasma science. The centers should have as a central objective establishing collaborations with new scientists with expertise of value to the plasma science and fusion research effort. An explicit goal of the centers should be to convey important scientific results to both the fusion and broader scientific community. Even the announcement of opportunity for fusion frontier centers would signal to the broader scientific community the intent of the fusion community to significantly bolster the scientific strength of the field.

It is highly desirable that there be interagency, and particularly NSF, collaboration in one or more fusion frontier center for reasons of disciplinary and institutional diversity as well as the benefits of interagency collaboration cited in (3). However, DOE should play a lead role in the fusion frontier centers, not only for sound reasons of administrative clarity but also because DOE leadership will ensure that the impressive technical capabilities of the present fusion energy science community will be made available to new participants. DOE leadership will also ensure that progress in the frontier centers would be communicated throughout the fusion community and translated into DOE program plans, to the benefit of progress towards the fusion energy goal.

The process for the awarding of grants for fusion frontier centers could do much to address the problem of isolation of the fusion science community by ensuring broad participation of the scientific community in the institution-building effort. The selection process for the centers should feature open, competitive peer review employing clear, science-based selection criteria.

The committee considered this recommendation to be critical enough to the new science-based approach to fusion energy that it recommended that ways be found to fund a first center even in a level-budget scenario. The success of the competition and the quality of the first center should be used as guides to whether to launch a second and third center. In other programs, such centers have been effective mechanisms for strengthening the breadth and depth of a broad scientific area. There is a very strong argument for expanding program funding to give fusion frontier centers a strong and durable foundation.

(5) Solid support within a broad scientific community for U.S. investment in a fusion burning experiment should be developed.

An eventual burning plasma experiment is scientifically necessary as well as being on the critical path to fusion energy. The determination of the optimal route toward a burning plasma experiment is beyond the scope of the committee; rather, the route should be decided in the near term by the fusion community. Resources above and beyond the present program will be required. The U.S. scientific community should take the lead in articulating the goals of an achievable, cost-effective scientific burning experiment and in developing flexible strategies to achieve it, including international collaboration.

The committee agreed with the SEAB report that "…development both of understanding of a significant new project and of solid support for it throughout the political system is essential." However, since the U.S. Fusion Energy Science program is now positioned strategically as a science program, advocacy by the larger scientific community for the next U.S. investments in a fusion burning experiment becomes even more critical to developing that support. For this reason alone, the scientific isolation of the fusion science community needs to be reduced.

(6) The National Science Foundation should play a role in extending the reach of fusion science as well as in sponsoring general plasma science.

The mission of OFES, following the restructuring of the program in 1996, has been to establish the knowledge base in plasma physics required for fusion energy. Consequently, a substantial number of plasma science issues are being explored within the fusion regime that also have applicability to allied fields

See "Fusion Science" on page 6

Fusion Science
(continued from page 5)

such as astrophysics. For this reason, the committee believes that NSF should begin to play a more significant role in the solution of these basic plasma science issues. The involvement of NSF could have an intellectual impact on basic plasma science similar to that which it has had on basic research in other scientific disciplines where mission agencies like DOE play the main funding role. NSF involvement would facilitate linkage to other fields and would also encourage the involvement of new scientists in the program.

Recently, NSF and DOE collaborated on a small but highly effective program to encourage small laboratory plasma experiments and theoretical exploration of topics in general plasma science. The large number of proposals to this program is an indication of the need for it. The rationale for the expansion of research in general plasma science was well articulated in the earlier NRC document *Plasma Science: From Fundamental Research to Technological Applications* (National Academy Press, Washington, D.C., 1995).

The NSF-DOE plasma science initiative, operated at a dollar level closer to that contemplated in the *Plasma Science* report (an additional $15 million per year for basic experiments in plasma science), can serve some important functions:
• Stimulating research on broad issues in plasma science that have potential applications to fusion; and
• Enhancing interagency cooperation and cultural exchange with regard to the approaches used by the two agencies in defining program opportunities, disseminating information on research results to the scientific community, selecting awardees, and judging the outcomes of grants.

The optimal process for this partnership, if given sufficient funding (as requested in the *Plasma Science* report), would be an annual solicitation of requests for proposals (RFPs). This process would be particularly important for maintaining opportunities for new PhDs to enter and stay within the field, since new PhDs are produced by degree-granting institutions each year and new graduate students enter school each year.

Another limitation of the ongoing NSF-DOE program in basic plasma science is the absence of a provision for modest-scale experiments in the $1 million per year class. Historically, neither DOE nor NSF has funded plasma science experiments of this scale. For this reason the committee recommends a cooperative NSF-DOE effort to broaden the scientific and institutional reach of fusion and plasma research. Such an effort would yield results of high scientific value. Increased NSF funding and a stronger organizational focus on fusion as well as plasma science within NSF would be required. As discussed in (4), a natural role for NSF would be cosponsorship of one or more frontier centers in fusion and plasma science.

(7) There should be continuing broad assessments of the outlook for fusion energy and periodic external reviews of fusion energy science.

The committee found the current pattern of multiple program reviews of different provenance to be excessive. A planned sequence of independent external reviews should replace this pattern.

The U.S. fusion energy science program should be assessed at regularly scheduled intervals. These assessments should be open, independent, and independently managed. They should involve a cross-section of scientists from within and outside the fusion energy program. The manifest independence of the review process will help ensure the credibility of the reviews in the eyes of Congress, OMB, and the broader scientific community.

The scientific, engineering, economic, and environmental outlook for fusion energy should be assessed about every 10 years in a process that draws upon fusion scientists, other scientists, engineers, policy planners, environmental experts, economists, and others, from the United States and abroad. These reviews should assess from multiple perspectives progress in the critical interplay between fusion science and engineering in light of the evolving technological, economic, and social context for fusion energy.

The committee did not take up the many critical-path issues associated with basic technology development for fusion or the engineering of fusion energy devices and power plants. It is the combined progress made in science and engineering that will determine the pace of advance towards the energy goal. Much of fusion science research is undertaken in the expectation that it will ultimately contribute to the energy goal. Regular, formal assessment of the progress towards fusion energy is one important way in which a fusion science program can be made accountable to the long-range energy goal.

Conclusion

It was a privilege and a pleasure to get to know fusion research at a critical turning point in its evolution. I hope that the different perspectives brought to bear on the future of the program by the committee, with its blend of practicing fusion scientists, active scientists in related fields, and scientists with broad managerial experience, will stimulate the fusion research community to reach out to the broader community of science and thereby assume its rightful place in the sun. ■

BPA Meeting
(continued from page 3)

physics. CAMOS is planning to place more emphasis on optical physics.

The meeting concluded with a brief discussion of the reorganization of the National Research Council that is now in progress. The BPA will be part of a new division that will be formed in January merging the Commission on Physical Sciences and the Commission on Engineering into the Division of Engineering and Physical Sciences.

The next meeting of the BPA will take place just before the National Academy of Sciences annual meeting, on April 27-28, 2001. ■

Physical and Life Sciences (continued from page 1)

fuel for much biological activity, from muscle contraction to the packaging of neurotransmitters in the brain. The ATPase molecule is embedded in a closed membrane, and the energy for ATP synthesis is derived from a difference in chemical potential for hydrogen ions between the inside and outside of this membrane. Remarkably, the ATPase not only couples the flux of hydrogen ions to ATP synthesis but also rotates in the process, and under the right conditions this rotation can be harnessed to do macroscopic work at near unit efficiency. Questions about how all this might work are brought into sharp focus by the availability of atomic resolution structural information on the ATPase from x-ray crystallography experiments. Oster described models for the coupling of mechanical and chemical changes, using methods from statistical mechanics. These models can be seen as part of a larger class of ideas that describe molecular machines ranging from actin and myosin in our muscles to polymerase molecules that copy and express DNA, hinting at more general principles.

As indicated in Galas' introduction, one of the major changes in biology has been the availability of large, and in many cases essentially complete, data sets. Dan Rokhsar (University of California at Berkeley and the DOE Joint Genome Institute) took on the task of surveying this progress and the opportunities that it creates. We all are aware of the large effort to sequence the human genome, literally reading the billions of "letters" along the DNA molecules that are folded into the chromosomes and packaged into the nuclei of every cell in our bodies. These techniques have progressed to the point where the entire DNA sequence of a small organism, such as a bacterium, can be read in a single day. Because all organisms share similar "hardware" at the molecular level, the possibility for large-scale exploration of multiple genomes will sharpen our view of the evolutionary tree and also hasten the discovery of universal elements in nature's toolbox of molecular machines. Exploration of genomic data, however, depends crucially on having an appropriate theoretical framework, providing clear challenges to the theoretical physics community. Even practical questions such as the statistical significance of similarities among different DNA sequences have an interesting formulation as problems in statistical mechanics. Rokhsar emphasized also that coming face to face with the whole genome highlights the physical issue of how this molecule is packaged in compact form inside the cell but still accessible so that information can be read out during the expression of genes to make proteins.

While significant fractions of the DNA sequence serve to encode the structure of proteins, much of the DNA serves other functions. Ideally we would like to read the DNA sequence and recognize that it breaks into segments with distinct functions, including, for example, providing sites where proteins can bind to regulate the expression or translation of nearby DNA into proteins. Breaking a continuous sequence into functional units is a bit like breaking a continuous stream of letters (no spaces) into words. Hao Li (University of California at San Francisco) discussed a statistical mechanics approach to this segmentation problem that leads to the discovery of (correct) words in novels and to candidate regulatory sites in the genome of yeast. These candidates can be tested in gene chip experiments, and at least in some cases the theoretical analysis has led to the discovery of new functional units in the DNA sequence. Li emphasized that theoretical ideas provide a bridge among many different large data sets, holding out the hope of a unified analysis based on single genomes, gene chips, and the comparison of genomes from related organisms. The analogies between language and DNA sequences are tantalizing and lead us to ask if there is a syntax or phrase structure beyond the individual regulatory words.

The power of modern biology derives from universality at the molecular level: humans and bacteria use the same genetic code, and many protein molecules are recognizable as homologs even between the most distant of evolutionary cousins. This universality extends even to the brain, where homologous molecular components (ion channels, transmitters, and receptors) are found in our brains and in those of earthworms, fruit flies, and slugs. In trying to give an overview of how physicists have been thinking about the brain, I emphasized that we are converging on a complete "parts list" for cells in the brain, together with nearly exact dynamical models for the role that these parts can play in electrical signaling and computation. One problem then is purely theoretical: how do we pass from a description of this dynamical system to an understanding of what one cell or small circuit can compute? At the level of neural systems, we face again a problem of coding, but now information (about the sensory world or motor actions) is represented by sequences of action potentials in populations of nerve cells rather than by sequences of bases in DNA. Recent work has shown how we can "read" this neural code and how it adapts to different situations. There are glimpses of general principles that might govern the selection of the code, such as optimizing the efficiency of representation, in effect using as much as possible of the entropy in the sequence to carry information. The same issues of entropy and efficiency guide modern theories of learning, which have had strong input from statistical mechanics.

One view of life is that it is no more and no less than a massive accumulation of detail over the history of evolution. Another view, which I think strikes a resonance in the physics community, is that the qualitatively striking phenomena of life should have correspondingly deep theoretical explanations. To the extent that physics sets itself the task of providing a predictive, mathematical description of nature, there is no reason for our discipline to create a division such that the phenomena of life are outside our purview. In practical terms, however, our enthusiasm for the phenomena has long been held back by the difficulty of doing controlled and quantitative experiments. But this situation has changed for the better. From single molecules to genomes to the dynamics of gene expression or networks of neurons, many of the striking phenomena of life can now be studied quantitatively and exhaustively. There is an opportunity for physics not just to contribute to the advance of biology but also to advance its own frontiers in the understanding of nature. ■

THE BPA Web site at **www.national-academies.org/bpa** provides news on recently released reports and other developments. Reports may be ordered at **www.nap.edu.**

New reports:

- *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program* (prepublication version)

Coming early in 2001:

- *Astronomy and Astrophysics in the New Millennium* (published version)
- *Physics in a New Era: An Overview*
- *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program* (published version)
- Report of the Committee on Physics of the Universe: *Connecting Quarks and the Cosmos: 11 Scientific Questions for the Next Century*

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