A Collective Vision for Physical Sciences at Berkeley

The Chancellor's Advisory Committee on Physical Sciences

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ABSTRACT

This standing committee was created in Spring 2019 to provide faculty input to campus leadership on opportunities for Berkeley to excel in scholarship and research across the physical sciences while building and supporting a diverse community of scholars. The committee meets under the aegis of the VCRO in consultation with the Chancellor, EVCP, and cognizant Deans, and includes membership across the College of Chemistry and the Division of Mathematics and Physical Sciences.

The first sections of this report highlight five areas of science that cut across departments and represent emerging opportunities for Berkeley to lead. These areas can also capture the public's imagination and maintain pride in Berkeley research. As the New Yorker put it, "California in its heyday managed to make genius public property." We would like Berkeley to remain the source of science and scientists that benefit all Californians.

While these five areas appear ripe for targeted investment, we emphasize that exciting research emerges most often not from planning at the top but instead from giving all faculty the time, resources, and independence to pursue the directions they find most likely to be productive. Two Berkeley examples recognized by this year's Nobel committee are the discovery of a supermassive black hole at our galaxy's center by Reinhard Genzel and the invention of CRISPR/Cas9 gene editing by Jennifer Doudna, which drew on studies of CRISPR in microbes by Jill Banfield of EPS.

With both large- and small-scale efforts in mind, we make five recommendations aimed at enabling Berkeley's continued excellence not just in scientific research but in the training of scientists. We start with how to attract a diverse group of talented, motivated junior scientists at the graduate and postdoctoral levels, and how to support their success. We then discuss the infrastructure, both physical and administrative, that excellent science requires, and conclude with ideas about how scientific directions such as those in this report can be developed into inclusive collaborations centered at Berkeley.

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1 *Introduction and Summary of Recommendations*

The importance of science in our daily endeavors has never been greater, and while our understanding of the physical universe advanced immeasurably in the past century, new challenges to our understanding continue to appear. We would like the tradition of groundbreaking, influential science at Berkeley to continue for another century—by maintaining what we believe to be a uniquely fertile environment for both collective "big science" and individual creativity. Scientific progress is not a zero-sum game, and its discoveries ultimately benefit everyone, which may be why it enjoys nearly universal support. American taxpayers have chosen to build, as the distinctive tangible monuments of our society, not cathedrals or pyramids but Kennedy Space Center and Fermilab. Scientific discoveries made at Berkeley continue to benefit the whole world. In this report, we will focus on basic science, but it should not be forgotten that the relative prosperity of nations and regions in our time derives in large part from their ability to harness science and technology.

The first section below is on **deciphering the universe and its origin**. For the first time in history, we have a broad understanding of the major events in the evolution of the universe from the Big Bang to the present day: the creation of the elements, the genesis of galaxies, nebulae, stars, black holes, and planetary systems and their relationships to one another. There are still important discoveries to be made as well as the big unknowns of the nature of the dark matter and dark energy that fills the cosmos. Essential elements of our understanding, such as detailed knowledge of how galaxies, stars, and planetary systems are born and evolve, must be clarified with ongoing research to ensure our general understanding becomes accepted knowledge. But the accelerated pace of discovery over the last half century has given us an excellent framework and a high degree of confidence that we can gain deep knowledge of events about which we could only speculate a few years ago.

We then turn closer to home, to **understanding our changing Earth**. Just as we begin to study planets outside our Solar System, our impact on our own planet from local scales to the global scale is becoming ever more apparent. We are increasingly aware of the ways we are changing the Earth because we can compare changes now to ways the Earth has changed in the distant past without human influence. At the same time, the complexity of the infrastructure upon which we depend is increasingly sensitive to our environment. While we face substantial challenges if we are to survive, the explosion in availability of sensors and data, together with the emergence of powerful new means of removing environmental contaminants, provide unprecedented opportunities for both discovery and remediation. We see three areas of particular promise for Berkeley to pursue: (i) developing new sensor arrays that provide better forecasts of future changes in our geo-space environment, atmosphere, water supplies, and land structures, (ii) utilizing this information to improve our ability to model changes and predict the impact of a mitigation strategy, and (iii) creating new materials and processes that enable the efficient removal of contaminants from air, water, and soil.

Of course, we must also seek to develop technologies that do not emit greenhouse gases or produce contaminants in the first place, by **accelerating materials discovery for a circular economy**. Recent developments in artificial intelligence, together with advances in automated synthesis, stand poised to revolutionize the ways in which we make molecules and materials. Indeed, by combining artificial intelligence, high-throughput robotic instrumentation, and new in situ techniques for monitoring the progress of a reaction, it is likely that the rate of discovery of molecules and materials that advance medicine, physics, and environmental remediation will be greatly accelerated. UC Berkeley and LBNL have led the way on many of these fronts individually, but we should seize the opportunity to integrate these methods via a broad-based effort to discover materials that enable a "circular economy", wherein valuable chemical feedstocks used to form polymers, batteries, magnets, and other materials can be fully recovered upon loss of functionality.

Living systems and how they have evolved are one proof of principle for how robustness and sustainability can be achieved in complex materials and molecules, but much of how they work remains to be understood. **Demystifying the cycles and currents of life** requires finding the fundamental principles that govern systems lying far from thermal equilibrium–the conditions where biology operates. Descriptions beyond equilibrium are also essential for a broad variety of problems in chemistry and "soft matter" physics. By integrating novel experimental techniques with our expertise in computing, optimization, partial differential equations, dynamical systems, and other theoretical and statistical methods, Berkeley is well positioned to address this challenge. The knowledge gained can be expected to provide insights into the cycles, currents, and energy conversions that underpin life and its evolution over the course of Earth history, and even to inform our understanding of the origins of life. More generally, fundamental questions in biology have often been answered by tools and insights from the physical sciences, and Berkeley should foster an environment where fruitful exchange is encouraged and enabled. The 2020 Nobel Prize mentioned in the preamble is a timely example of such exchange between earth science and biology.

Understanding the quantum nature of the atom led to revolutions in physics and chemistry, and ultimately to the age of electronics and information technology. It is now becoming clear that the improved understanding of entanglement and other "quantum information" concepts is **enabling the second quantum revolution,** leading to powerful new means of transmitting information that are revolutionizing communications, computing, and sensing. Quantum information is also changing how we think about many fundamental aspects of the physical world. Experimental progress in quantum information will entail the discovery of new ways of creating, positioning, and manipulating qubits—the fundamental operating units of a quantum computer—spanning atomic and solid-state physics. Tools enabled by quantum information science are altering fields ranging from chemistry and earth science to engineering, biology, and medicine.

The last two sections of this report cover ideas for supporting science on campus that cut across disciplines. That discussion also allowed us to identify what we believe are crucial aspects of Berkeley science that must be protected even in a time of financial challenges. The resulting recommendations are as follows:

Developing the Next Generation of Scientists

Diversifying the Physical Sciences: Diversity at all levels is essential to the health of our physical sciences program, and action must be taken to improve representation. In particular, we recognize a loss of diversity at the level of postdoctoral scholars, who are essential to our scientific endeavors and who subsequently populate faculty positions. We therefore recommend that campus work to improve the environment for postdoctoral scholars and consider creating new postdoctoral fellowship opportunities for candidates who will diversify the professoriate.

Sustaining Excellent Graduate Programs: Targeted fund-raising is rapidly increasing graduate student fellowship support in the physical sciences at our peer institutions, and it is crucial that Berkeley at least match this effort. Financial questions, such as how best to offer attractive GSI/GSR packages to students and whether the current approach to indirect costs is ideal for maintaining an effective research environment, were not a major subject of our retreat. However, these issues are clearly central to the success of physical sciences at Berkeley, and we recommend that this committee be consulted and allowed to offer an opinion on proposed financial changes of relevance to our graduate programs. Students who would contribute greatly to Berkeley will look elsewhere if current trends continue, and their choices are directly coupled to the infrastructure challenges below.

Building Research Infrastructure: Facilities, Tools, and People

Facilities and Tools: Emerging physical scientists will choose universities that can offer the tools and other infrastructure necessary to pursue the frontiers of knowledge. Our campus infrastructure, including both research laboratories and experimental equipment, is currently insufficient to sustain our excellence in the physical sciences. We recommend that a subcommittee of this committee be formed to advise campus leadership on establishing priorities for improving campus access to essential experimental tools and for modernizing campus infrastructure for physical sciences. That committee may also wish to consider cost recovery and other funding sources to enable those investments.

Administrative Infrastructure: We concur with the concern expressed in a recent life sciences report that business functions are soaking up an increasing amount of faculty time. Improvements would benefit both large collaborations and smaller efforts, and Berkeley needs to foster an environment in which faculty can pursue the directions most interesting to them. An efficient administrative infrastructure should free up faculty time to teach, mentor students, and pursue new directions that may become the major scientific initiatives of tomorrow.

Creating New Research Partnerships: Understanding that faculty are frequently overcommitted, it can be challenging to devote the time and energy needed to organize groups of colleagues around large-scale multidisciplinary (and often multi-institutional) funding opportunities. We recommend that campus provide support for workshops that will galvanize our research community in potential priority areas of the physical sciences, including those enumerated above. These will facilitate our institutional response to large funding opportunities by allowing teams to develop organically and inclusively, while also benefiting individual research efforts. Support could also take the form of seed grants to encourage faculty to engage in new directions and/or strategic areas in the physical sciences.

2 *Deciphering the Universe and its Origin*

Big Bang cosmology tells us that the universe originated from a tiny point of enormous density and temperature expanding over the course of about 14 billion years to become the cosmos we see today. All the exquisite structures seen through our telescopes–the galaxies, stars, nebulae, and planets—-as well as the elements that make them up, protons, electrons, and neutrons as well as the atoms assembled from them—condensed from an amorphous soup over the course of time as the universe grew larger and cooled.

Big Bang cosmology unified our study of the universe similar to the way the theory of evolution unified and transformed biology. The evidence for this remarkable story is overwhelming. It is possible to calculate when and how these structures emerged and predict consequences for their properties imprinted on the cosmos that we observe today. The extraordinarily high accuracy with which we can observe the salient structures and confirm their match to the predictions of Big Bang cosmology led to today's broad consensus on its validity. It has transformed the subject of astronomy and is a triumph of modern science no less profound than the realization that the Earth is only a minor object in the solar system, itself a minor collection in the galaxy of billions of stars that emerged after Copernicus' ideas and Galileo's discoveries 400 year ago.

There are, nevertheless, major unknowns that must be resolved before we can declare our understanding of the universe to be on sound footing. The first two are the nature of the dark matter and dark energy that together comprise more than 95% of the universe, with the ordinary matter we know making up the other 5%. A third concerns the large-scale uniformity of today's universe, thought to result from an early period of rapid acceleration called inflation, that is not tied to dark energy. It is equally important to test our understanding of the structures in the known matter—the galaxies, stars, nebulae, and planets—to ensure that we understand the objects producing the light that is used to study the properties of the universe, work that makes up much of modern astronomical research. And we would like to know if life in the Galaxy is common or rare.

Scientists at Berkeley made many of the seminal advances leading to today's consensus. In the 1990's, Berkeley scientists confirmed the Big Bang picture beyond any doubt with precise measurements of the cosmic microwave background leading to a Nobel Prize in 2006 for a Berkeley professor, George Smoot. Dark energy was discovered by Berkeley scientists, one of whom, Saul Perlmutter, received the 2011 Nobel Prize for his work. Berkeley astronomers made many of the critical observations of universal structures to determine the origins of galaxies and stars, the existence of black holes including an enormous one at the center of our galaxy (recognized by Reinhard Genzel's 2020 Nobel Prize), the physics of interstellar matter, and the ubiquity of planetary systems around stars other than the Sun. Berkeley astronomers working with nuclear physicists helped give us our understanding of how stars produce their energy, how supernovae explode, how black holes are created, and how to use this understanding to test other predictions of cosmology, since almost all observations rely on a deep knowledge of the objects producing light that we can see.

Berkeley remains well positioned to lead the advances in the coming decades. The departments of astronomy, physics, and Earth and planetary sciences collaborate well through joint appointments, organized research units and their affiliation with Lawrence Berkeley National Laboratory. Berkeley researchers are tackling all the big questions outlined above, including experiments to detect dark matter, observational programs to study dark energy and its effects on space-time, observations of black holes, planets, stars, nebula, and galaxies as well as studies of the large-scale distribution of matter. We have active programs to study exoplanets, a precursor to detecting extra-terrestrial life outside the Solar System.

Scientists at Berkeley benefit from preferential access to unique facilities such as the Lick and Keck Observatories, and previously the Berkeley Interferometric Millimeter Array (BIMA). These in turn aid them in competitive proposals to use open access facilities such as the Hubble Space Telescope (HST) and the Chandra X-ray telescope. Berkeley's involvement in the Thirty Meter Telescope consortium means that its researchers will also have access to the TMT when it becomes operational. Nevertheless, the field of astronomy is moving increasingly to reliance on very large international facilities that do not grant preference to individual institutions. This trend is similar to what happened in particle physics research, suggesting that astronomy is likely to change in ways that physics pioneered: larger collaborations and consortia, less preferential access to the largest facilities, and new instruments and facilities requiring years of effort and hundreds of millions to billions of dollars to build. Berkeley should plan a strategy to adapt to this trend.

The Moore's law growth in detector capabilities means that almost all new facilities generate enormous quantities of data. Researchers adept at mining large data sets to make discoveries and carry out experiments will have an advantage in this world. The Division of Computing, Data Science, and Society along with the local access to supercomputers through LBNL and even industry (e.g. Google and Amazon) should contribute strongly to Berkeley's competitive position for carrying out research on the universe. Large scale numerical calculations are becoming an important component of theoretical research. The interplay between theory and observation enabled by large scale computing and application of machine-learning techniques to science is well suited to Berkeley's evolving faculty and culture of interdisciplinary research.

Finally, we are coming into a second space age with the creation of many new rockets by entrepreneurs: Space-X, Blue Horizons, Rocket Labs and others promise to dramatically increase the frequency and lower the cost of access to space. Berkeley's Space Sciences Laboratory provides its researchers with the ability to build spacecraft and space instrumentation on campus. This is an enormous advantage that should be a benefit for many fields of scholarship only a fraction of which are using it now. Judicious investments in faculty with an interest in space experiments are a natural way to diversify Berkeley's research and keep it at the forefront in understanding how the universe was created.

3 Understanding Our Changing Earth

Humanity's impact on the Earth system is becoming ever more apparent. There are now numerous examples of global scale changes in atmospheric composition caused by human activities that are altering the chemistry and dynamics of the atmosphere and ocean, Earth's surface temperature, the water cycle, sea level, and the complex interactions between them. Turning this knowledge into an understanding of how the Earth system will continue to evolve, and how we might mitigate the consequences of that evolution, is a major challenge for current science. Research on how past changes took place will be crucial to that understanding: the Earth's past is key to predicting its future.

In particular, the past is the best source of reliable information on how to build models that can help us understand consequences for society, especially those times in which Earth may have experienced changes in climate and underlying climate drivers as rapid as today's. Such studies will inform both policy and engineering solutions for dealing with climate change, as well as other hazards such as earthquakes and volcanism, since such solutions require a strong science base.

We have not achieved, for example, sufficient understanding of how regional-scale climate is likely to evolve over the next decades in order to predict societal impacts such as crop failures that in turn may drive large-scale migration in the developing world. In the US, the complexity of the infrastructure upon which we depend is increasingly sensitive to our environment. The significant impacts of climate change are already apparent. Sea level rise is already providing tragic examples of how some of the world's poorest people are suffering as a result of actions in the developed world. We have a moral responsibility to avert the worsening consequences, building on our knowledge of the past to develop predictive models, and then turn to engineering or policy measures to ameliorate them.

While we face substantial challenges in surviving turbulent changes on our planet, the explosion of sensors and data provides unprecedented opportunities for new discovery. But to be successful in maintaining our future stability, we must couple new observations with the development of new theory. We must link our physical models of planet Earth, with engineering strategies to sustain our infrastructure. We must guide responsible public policy and regulation to provide the necessary incentives to ensure our future. We can then turn to different sorts of measures to change the Earth's future from the course it would otherwise follow. One can draw hope from a prior example of how atmospheric chemistry impacted policy: the global effort to ban chlorofluorocarbons (CFCs) via the Montreal Protocol originated in the work of scientists who were recognized by the 1995 Nobel Prize, including Berkeley Ph.D. alumnus Mario Molina.

There is undoubtedly a role for policy and engineering solutions in alleviating some kinds of geophysical hazards. However, for the example of climate change, there are challenges in basic chemistry that could be effective and practical complements to policy interventions such as switching energy sources. The dominant human-induced change relevant to global warming is the increase in atmospheric carbon dioxide concentrations. If we could find efficient industrial-scale means to remove atmospheric carbon dioxide using chemistry, similar in spirit to the planting of trees but building on Berkeley's strengths in developing and commercializing molecules and metal-organic frameworks, we would have the ability to slow or even reverse this effect even without a universal commitment to reduce carbon-dioxide-generating fuel use.

Of course there remain many areas where geophysical and geochemical inquiry at the individual investigator level remain the best way forward, and not all of earth science is about hazards. But we would like to highlight three particularly important areas requiring this coordinated combination of measuring the Earth's current and previous states, developing predictive models, and creating science-based approaches to mitigation:

- *Climate change and our response.* We know the climate is changing. We see the impact of increased sea level with more frequent and severe coastal flooding. The West Coast is painfully aware of increased fire risk as even people not directly affected by the fires are affected by hazardous air quality and expensive or elusive homeowner's insurance. But what should we expect in coming decades, and what are our options to prepare for and mitigate these effects?
- *Earthquakes, landslides and deformation of the "solid" Earth.* The ground upon which we build and depend is moving—sometimes in sudden violent ways, but rarely in unexpected ways. New sensor arrays provide better forecasts of future movement, and warning of imminent threats.
- *Environmental degradation and remediation.* We must now clean up the pollutants that we have emitted across our environment. Whether it be CO_2 removal from the atmosphere, or pollutant removal to secure our food and water supplies, there is currently a disconnect between discovery of new techniques in science and the engineering of solutions, with room for improvement in the translational process.

Berkeley is uniquely situated to reach across the multiple disciplines necessary to both make the discoveries necessary and see them implemented in effective ways. However, improvements to our basic research infrastructure in some areas are needed, particularly within the earth sciences. We could also organize more effectively for external opportunities as described in another recommendation. Perhaps most of all, our campus-level actions need to reflect that policy and engineering depend on a core of scientific understanding, that the science of how our Earth is changing remains far from complete, and that whether Berkeley leads in that area of science remains in the balance.

4 Accelerating Materials Discovery for a Circular Economy

Modern humans have existed as a species for a few hundred thousand years, which is the blink of an eye in geologic terms, and human civilization arose only 10,000 years ago when Earth's climate warmed and stabilized after the last Ice Age. Yet it is unclear that our current way of life is sustainable for even a few centuries. Scientific advances are needed if we are to achieve the goal of a society that is truly sustainable in how we use materials and molecules. Increasing atmospheric carbon as noted in the preceding section is just one example; we need to create eventually a "circular economy" where our inputs and outputs are balanced rather than creating ever-aggregating piles of waste products, and in the meantime improve our use of scarce inputs over the full cradle-to-grave life cycle.

The synthesis of new molecules and materials has been a key driver of science and technology since the Bronze Age, but there is the promise of a genuinely new approach that would help us address sustainability and other challenges. Recent developments in artificial intelligence, together with advances in automated synthesis, stand poised to revolutionize the ways in which we make chemical compounds. Indeed, by combining artificial intelligence, cutting-edge high-throughput methods for synthesis and characterization, and new *in situ* techniques for monitoring the progress of a reaction, it is likely that the rate of discovery of molecules and materials that advance medicine, physics, and environmental remediation will be greatly accelerated. UC Berkeley and LBNL have led the way on many of these fronts individually, but it is essential that we now seize the opportunity to integrate these methods and establish leadership in the generation and discovery of new forms of matter. This will require a significant investment in state-of-the-art platforms for synthesis and characterization, as well as in hiring new faculty who are capable of working together across disciplines to make the most of this rapidly progressing technology.

Berkeley has a long history of large-scale research initiatives in energy, including Helios, JCAP, and others.

There has been great progress in renewable energy, but now other aspects of the circular economy are moving to the center. We will need to consider new classes of materials that can be recycled or reconfigured and are responsive towards external environments and stimuli. We need to develop new ways of thinking about chemical bonding that likewise are reconfigurable and responsive to their environment. Finally, we need to invent greener ways to make plastics and other materials with effective ways to decompose or recycle them.

It is time to have a campus-wide initiative along the lines of "Science for the Circular Economy", going beyond our traditional renewable energy focus; it will bring together researchers in chemistry, physics, earth and environmental science, engineering and policy. This would build on our established strengths across STEM departments and on important recent discoveries, such as new kinds of low-dimensional materials and new approaches to microscopy. It would also build on our historically strong links with LBNL in this area, and the unique facilities available there, including planned facilities on Charter Hill near the Advanced Light Source.

There are potential weaknesses that need to be addressed. As mentioned in Section 8 below, no state-of-art shared facilities for research in this area exist on campus. LBNL primarily hosts national user facilities, to which Berkeley faculty members do not have privileged access. Having a better research facility for chemistry, materials science, and some areas of physics would make proposals in this field more competitive. The "Future of Biology" mentioned the possibility of multiple investigators sharing a single laboratory; it may be beneficial to the physical sciences to consider some shared equipment models.

While investigators in this area have both federal and foundation (Kavli ENSI) support, currently there is no campus-wide energy initiative like those at Stanford/MIT, for which industry support could be crucial. The breadth of research in this area also highlights some opportunities for growth in how campus prepares for and responds to large-scale funding opportunities. Specifically in the materials area, it is worth mentioning that we have not succeeded in attracting an NSF MRSEC (Materials Research Science and Engineering Center), despite many efforts involving considerable work by the PIs. A reason sometimes given for this lack of success is the availability of funding for materials research through LBNL, which again raises the issue of whether campus is meeting its responsibility to those faculty whose research does not fit into the DOE/LBNL mission; while we may not be able to replicate LBNL for them, we should be able to provide those faculty with opportunities comparable to those at other UC's, and it appears we are not.

The payoff for reinventing how we discover new molecules and materials could go well beyond creating a circular economy. Predicting the behavior of materials tests the limits of our understanding of quantum mechanics, and finding new materials has historically led to both unforeseen applications, for example in information technology, and new understanding of basic quantum physics (Section 6). Biology provides ample proof that sustainable complex architectures are possible, which leads to our next topic.

5 *Demystifying the Cycles and Currents of Life*

The Earth is an example of a complex, constantly evolving system. At a smaller scale, biology provides examples of microscopic functionality that, in many cases, far outstrip what we can achieve in synthetic systems. Some of these examples demonstrate exquisite coordination of molecular and mesoscale components, e.g., molecular motors that convert chemical energy into concerted motion which directs cargo within a cell. Other examples highlight the possibilities of stabilizing robust non-covalent (i.e., weakly bound) structures within extremely noisy environments. Still others harness natural fluctuations in molecular organization to achieve complex responses to subtly changing conditions. Each of these feats, in a synthetic context, would amount to overcoming a grand scientific challenge. Inferring principles of chemical and physical design from biological systems is thus an exciting and inspiring area. When successful, such efforts can also serve to improve the efficiency and depth of biological research.

A second exciting direction is to address a substantial gap between quantitative approaches for solving biological problems. The field of biophysics historically adopts and extends tools drawn from the cutting edge of physical research, aiming to establish a mechanistic understanding that connects biological function to basic physical principles. The field of bioinformatics, by contrast, draws primarily on sophisticated tools of statistical inference to address more specific questions of practical importance to biological research. Work that combines the two in a profound way is nascent. Doing so could dramatically enhance the impact of mechanistic biophysics. Machine learning, and neural networks in particular, might play an important role in this bridging effort. Expertise in machine learning spans many departments at Berkeley, from chemists inferring molecular mechanisms through neural networks trained on massive surveys of reactivity to mathematicians exploring how and why such models work. More generally, integrating state-of-the-art high performance computing, optimization, partial differential equations, dynamical systems, mathematical physics, algebra and combinatorics to solve frontier problems in biophysics is an opportunity Berkeley is well positioned to lead.

A third exciting thread within this area, concerning the physical behavior of systems pushed far from equilibrium, connects extensively with other efforts in the mathematical and physical sciences. The framework of equilibrium thermodynamics, and its mathematical foundations, has served as a touchstone for generations of work in chemistry, physics, earth science, and biology. In a biological context, this perspective requires an uncomfortable and sometimes ill-founded assumption: As has frequently been noted, biological systems at equilibrium are simply not alive. The cycles, currents, and energy conversions that fundamentally underlie life are disallowed at equilibrium. In comparison to the power of equilibrium thermodynamics, a framework for quantitatively describing such currents does not yet exist. But promising seeds have recently emerged, e.g., fluctuation theorems that generalize aspects of the second law of thermodynamics, a general mathematical structure for the statistics of large deviation, and efficient computational tools for dissecting nonequilibrium response. Research that unites these advances is an opportunity for which Berkeley is well-poised, and one that could open new perspectives in biology. The beginning of life, after all, is essentially the initiation of currents and cycles; the theory of natural selection that has shaped modern biology offers little guidance for understanding the roots of this origin.

The degree of self-organization in biology is much greater than anything else we know of in the universe. At the highest level, descent with modification and natural selection, otherwise known as Darwinian evolution, can explain the progress of biological evolution subsequent to the development of individual organisms that compete for resources and reproduce. This principle does not operate in physics or chemistry. By itself, it is inadequate to explain how molecular reactions organized themselves to give rise to cells, presumably the first living entities. The leap from physics and chemistry to biology demands an understanding of how self-organization can emerge from the relatively disorganized chemical environment on the early Earth, albeit one with abundant flows of energy and matter that were needed to drive the emerging order. Understanding the (probably several) organizing principles necessary to create this leap is squarely in the realm of physical science research and stands as one of the pre-eminent scientific questions of this century.

Revolutionary areas of particular overlap between physical, biological, biogeochemical, and mathematical sciences include imaging technologies and DNA sequencing analysis (which has become heavily statistical and computational in nature). The impact of advances in characterization of (bio)materials with increasing spatial and temporal resolutions (e.g., superresolution fluorescence microscopy and cryo-electron microscopy) on biology cannot be overstated and promises to continue. Another area enhanced by interactions between physical and biological sciences and engineering is towards engineered materials for biological applications (e.g., organ on chip; tissue engineering; bio-inspired adhesives, etc.) with significant societal implications.

Berkeley has a strong core for competing in all of the areas described. A discussion among our relevant experts would be best to identify where a small investment could achieve critical mass, and whether it might be worthwhile to bring in faculty through a targeted process. In particular, existing structures often do not favor open faculty searches based on broad but well-defined themes. Such searches offer many benefits, including better prospects for enhancing diversity, and could incorporate lessons drawn from previous interdisciplinary searches. This area could be a useful test case for the ideas about constructing centers in our last recommendation, such as one-day workshops to identify new directions and collaborations. Some preliminary investigations in classical non-equilibrium systems are relatively inexpensive and could be started with seed grants or fellowship-funded graduate students. The intersection of physical and biological sciences is a significant opportunity to build on Berkeley's strength in both fields and create a thriving community, which might differ from previous efforts in being less directly focused on near-term applications to medicine or bioengineering and more about combining techniques to address fundamental and long-standing questions.

6 Enabling the Second Quantum Revolution

The first quantum revolution started with basic science in the first decades of the 20th century. This new way of thinking about the physical world shattered the philosophical notion of a deterministic "clockmaker's universe". It also enabled revolutionary technologies such as the transistor, the nuclear reactor, and the laser. The second quantum revolution is now underway, as more subtle properties of quantum mechanics such as entanglement are fostering new research directions, not just in the physical sciences but in mathematics, computer science, and engineering. This revolution is already challenging our basic notions of information, computation, and privacy, at the same time as it answers fundamental physics and astronomy questions such as how black holes work.

Berkeley is already positioned to lead in applying the new concepts of quantum information to basic questions and to the development of quantum technologies. However, the emerging field of quantum information science crosses traditional academic and funding agency boundaries. We give three areas in this section where the second quantum revolution is generating new research links. But first we provide a brief snapshot of how modern quantum research currently appears in many unexpected places on campus outside its traditional home in physics and chemistry. Earth scientists combine experiments using quantum sensors with computation using quantum Monte Carlo algorithms to understand materials subjected to enormous pressures in planetary cores. Computer scientists design algorithms to run on quantum computers, which replace the two-state bit of standard computers with a "qubit" that can be in infinitely many physically distinct combinations of those two states. Quantum technologies for communication and sensing are actively researched and applied in several engineering departments.

An adaptive and integrated strategy will be necessary for Berkeley to realize its considerable potential in this field as the multi-agency National Quantum Initiative gathers steam and many corporations jump in. Berkeley faculty lead multiple recently funded quantum centers, but some cross-cutting improvements could help in executing on current plans and developing future ones. We give a brief overview of three broad areas of quantum research: quantum coherent devices, quantum information theory (and interfaces between quantum mechanics and the mathematical sciences more broadly), and quantum matter.

- *Quantum coherent devices.* One of the deepest aspects of quantum mechanics is a beautiful synthesis of the discrete and the continuous that changes how we think about information. Thinking about how to store and manipulate information in qubits enables truly new approaches to computation, communication, and sensing. For example, quantum computers can break classical codes currently used to protect privacy, but quantum cryptography could ensure secure communications by a new physical mechanism.

  Berkeley can claim several foundational accomplishments in quantum devices. Spin echo, a technique to maintain quantum coherence that is widely used in MRI machines, was invented here, and the first demonstrations of macroscopic quantum coherence in superconducting devices took place in Berkeley laboratories. Quantum devices will continue to find a broad variety of applications, not least in helping answer the other big science questions in this document.

- *Quantum mathematics, physics, and computer science.* While the goal of understanding the laws of physics is *a priori* distinct from that of understanding mathematics, mathematical concepts are always found at the heart of physical sciences research. The transfer of tools and ideas is not a one-way street: quantum physics continues to lead mathematicians to think about mathematical objects in new and productive ways, driving progress in many areas of mathematics. The present report is primarily about the physical sciences, but these have always had a close relationship with the "theoretical" or "logical" sciences, such as mathematics, statistics, and theoretical computer science.

  Representation theory and analysis played a key role in the development of quantum mechanics since its early days. Topological ideas played a pivotal role in discovering several new phases of matter that are relevant for quantum applications. Theoretical computer science is another area where ideas motivated by physics have had tremendous impact, leading to a new understanding of computation. The linkage between the physical and logical sciences is deep, and it continues to be fruitful for both sets of disciplines. Quantum research is just one example of how physical sciences can link to Berkeley's broad strength in mathematics, computer science, and statistics, including unique facilities such as the Simons Institute for the Theory of Computing (SITC) and MSRI (Mathematical Sciences Research Institute).

- *Quantum matter.* When many quantum-mechanical particles are brought together, new collective states emerge. In other words, quantum behavior is not limited to isolated small objects, but is also fundamental to the behavior of superconductors and magnets, atomic condensates, and nuclear matter in astrophysics. Quantum collective behavior may even be fundamental to essential biochemical processes like photosynthesis. Recent work on "quantum emergence" has shown that new principles emerge not just in equilibrium systems but also those far from equilibrium, and the collective behavior of many particles enables new approaches to quantum sensing and computation.

We feel that considerable progress could be made by closer integration between the atomic, chemistry, solid-state, and theory communities, and between related centers/programs such as the Center for Quantum Coherent Science (CQCS) and the Simons Institute for the Theory of Computing (SITC). Right now, diverse communities tend to come together when needed for an external proposal, but aspects such as ongoing education and research activities are not as strong as they could be. Investments in shared equipment, perhaps in conjunction with LBNL or other partners, could bear fruit rapidly, as could connections on the theoretical side between physical scientists, mathematicians, and computer/information scientists.

The understanding that quantum information is here to stay, as a key concept and unifying theme across theoretical physics, chemistry, and computer science, is already leading to changes in how university research programs are organized. The quantum area seems like a natural target for fundraising and external partnerships. "Glue" activities spanning education and research could be targeted, perhaps coordinated through CQCS or SITC. Berkeley tends to attract revolutionaries, and it is a viable goal for Berkeley students and faculty to lead the next quantum revolution.

7 Developing the Next Generation of Scientists

Diversifying the Physical Sciences: The year 2020 has served as a reminder, if one were needed, that vast numbers of Americans do not share equally in the benefits of our society. STEM education opens a remarkable variety of doors to interesting careers, but the US is failing, at all levels, to educate a sufficient number of people in these fields, and those failures are disproportionately acute for women and underrepresented minorities. We will focus in this report on issues related to diversity in the professoriate, per our initial charge, but that should not be taken to mean that there is not equally important work to be done in other areas. We are pleased to note that Berkeley has taken great strides in recent years, and yet we have a great distance to go in establishing equitable access and outcomes.

There is general support among current physical sciences faculty for DEI goals. We took pride in the Physics Department's decision to unname LeConte Hall and in the naming of Berkeley's newest dormitory for David Blackwell, a mathematician who was Berkeley's first tenured Black faculty member. Facilitating access to a life in science for Black, Latinx, Chicanx, and Indigenous students, as well as those from other minority and minoritized groups, first-generation college students, and women is a high priority for campus leaders in the physical sciences. It is not a new priority, e.g., the College of Chemistry has been a national leader in developing successful strategies for equitable career outcomes for students for many years, and Berkeley Physics was many years ahead of its peers in hiring women as students and faculty. Berkeley also has a noteworthy history of departmental leadership by women in the physical sciences. The scientific community has gained from Berkeley's understanding of the dynamic interdependence of excellence and diversity whenever we have successfully acted on that knowledge. For example, Berkeley has been for several decades a national leader in the recruitment and advancement of doctoral students of color in the physical sciences, and is widely acknowledged for its leadership in developing model programs such as the Berkeley Edge and the California Alliance.

Looking forward, we consider faculty hiring and promotion to be an important area for action. While we recognize the deep connection between efforts to diversify along the entire academic path from undergraduate, to graduate student, to postdoc, faculty, and scientific leader, for this report, we consider it most urgent to address a particular career stage–postdoctoral researcher–where we feel the focus on diversity has been neglected (nationally and at Berkeley), where we feel there is a need for rapid action, and where such action is likely to have a profound and lasting impact. The full range and complexity of DEI issues at all STEM career stages would certainly justify a report of its own.

To frame this discussion, we would ask the administration to consider treating STEM faculty and departments as key to solving DEI challenges rather than part of the problem. Our faculty feel a sense of urgency and deep commitment to diversifying the scientific community at every level on campus, in the next generation of scientists, and in national and international contexts where we hold leadership, set standards, and exert tremendous influence. In relation to hiring, using diversity as a reason not to hire in STEM fields, or to minimize the role of faculty in the hiring process, both of which have happened in recent years, is doing Berkeley a considerable disservice and creating a short-sighted loss of opportunities. Every discipline struggles with structural inequities in American education and culture, and those inequities are well known to be most acute in fields requiring lengthy technical preparation. It is vital to the health of the campus, California and the nation not to diminish our STEM departments, not to attempt to wrestle control of their intellectual purview from them, nor to minimize their role in campus planning or fundraising exercises, but rather to grow them and, in that process, not to shrink from adopting sophisticated means to transform their demographics to the fullest extent possible given the availability pools of highly qualified scientists.

Facing the DEI challenge head on requires the administration to partner with STEM departments in achieving this, providing the necessary resources and support. Berkeley is one of the largest, and perhaps is indeed the largest, contributor of faculty to the nation's research universities. Yet, there is more danger of a decline in our STEM departments in ways that simultaneously diminish our ability to lead both in DEI and scientifically now than at any time in memory. We ask the campus to engage fully with us in the formidable but achievable quest of generating lasting change to the demographics of the STEM graduate, postdoctoral, and faculty levels. The vast majority of Berkeley STEM faculty are aware that our departments run the risk, if we are complacent, of presenting an unwelcoming, or even hostile, environment for women and people of color at all levels. Over time, our departments have become increasingly attuned to ways in which bias and exclusion operate, both directly and indirectly for members of groups underrepresented in science. In recent years, the social science that explains how racist, sexist, and other social prejudices and economic disparities intrude into institutional structures and professional relationships have helped to clarify why science has not more rapidly diversified. Our departments actively use this knowledge to develop new approaches in teaching, learning, and mentoring that are inclusive and result in equitable outcomes.

The pathway to a STEM faculty career is already difficult enough for all who attempt it, without creating additional difficulties. The feelings of isolation and career instability are greatest at the postdoctoral level, when Ph.D. scientists work for a few years in a single laboratory. This existing problem has been greatly aggravated by the COVID-19 crisis, and the return of theoretical/computational postdocs to campus to do their work remains a challenge. In the current system, there is little effort to make Berkeley postdoctoral researchers, with a few exceptions like the Miller fellows, feel like part of anything larger than their research group. The way that most postdocs navigate to their positions, which is fraught with ambiguity and uncertainty, and the ways in which they are supported, which is usually via a specific short-term research grant, are serious detractors to many members of underrepresented groups whose ambitions through the years of prior education are to advance to the professoriate. These structural problems, which are pervasive across the sciences internationally, place an enormous emphasis on graduate students to develop reliable, trusted professional networks, and put them in positions of extraordinary dependency on their thesis advisors. For both the postdocs and the postdoc mentors, these conditions demand immediate research productivity, which in turn leads to hiring based on expediency, to the exclusion of any other considerations–especially contributions to diversity. The largest single unaddressed diversion off the path to the professoriate for women and underrepresented minorities in STEM is at the postdoctoral level, through a combination of factors including the uncertainty of an academic career and the pressure to publish rapidly and impactfully.

This problem is common to all research universities and a collective solution is warranted. To effect change in this system requires not only collaboration between the peer institutions that supply each other with graduate students for postdocs and postdocs for faculty, but also robust recruitment and flow of URM scholars into the exchange, incentives for faculty to use the exchange mechanism to identify and hire scholars, inclusive hiring practices for postdocs, and strategies for ensuring the scholars are visible and considered for advancement to their next stage. Fortunately, Berkeley, this year, assumed leadership of a new national collaboration to do precisely this. Using a proven and cost-effective approach that has been led by Berkeley at a small scale, the approach will be refined and greatly expanded to scale in the next few years. The approach is an extension of the California Alliance experiment (Berkeley, Stanford, Caltech, UCLA), later joined by five new partners (U. Michigan, Harvard, Georgia Tech, U. Texas at Austin, and U. Washington), now called the Research University Alliance. The campus will benefit from this alliance to the extent that it contributes to it. The mechanisms being put into place are designed to identify exceptional candidates for postdoctoral and faculty positions who are URMs, but our campus will be in a position to recruit them only if we can compete with our peer institutions to support them. Already, Harvard, the University of Washington, and Stanford are establishing a funding base and instituting new approaches to recruitment of the pool of candidates that will emerge through this alliance. We ask the campus to help us gear up now so we are in the running to attract these postdoctoral and faculty candidates for Berkeley.

Once postdocs arrive, a silver lining of unionization may be that it increases our ability to reach all postdocs and let them know what immediate resources are available and what future careers are possible. Making the postdoctoral period a more fulfilling one and letting postdocs know that there is light at the end of the tunnel will have a dramatic effect on the composition of the scientific community. We should ensure that postdocs on reaching Berkeley are not left to their own devices but understand themselves to be part of a supportive science culture.

Recommendation: Diversity at all levels is essential to the health of our physical sciences program, and action must be taken to improve representation. In particular, we recognize a loss of diversity at the level of postdoctoral scholars, who are essential to our scientific endeavors and who subsequently populate faculty positions. We therefore recommend that campus work to improve the environment for postdoctoral scholars and consider creating new postdoctoral fellowship opportunities for candidates who will diversify the professoriate.

Sustaining Excellent Graduate Programs: At the time of writing, Berkeley's graduate programs in the physical sciences remain an impressive example of "comprehensive excellence", as measured in rankings such as those by the National Research Council. Berkeley is the only public university that competes for students with the leading private universities in essentially all areas of the physical sciences. These graduate programs are, however, facing a number of threats, and faculty sense a degree of complacency in dealing with these threats. It could seem unclear why the physical sciences might depend more for their research success on graduate programs than other areas of campus. We outline some reasons for this dependence below, while keeping in mind that the appropriate measures will vary between the seven departments within our committee.

Leaving aside the importance of graduate thesis research in its own right, graduate student researchers (GSRs) are more essential to the success of faculty research in the sciences than in other fields; this is particularly true in laboratory, group-based research, including collaborations that lead to discoveries as described in chapters 2-6. The duration of a Ph.D. allows GSRs to investigate new methods and take risks that are difficult within the short duration of a postdoc. Unfortunately, over more than a decade, Berkeley has seen a significant decrease in the number of paid GSRs. One contributing factor is the steady increase in graduate student tuition, which makes it more efficient for faculty to spend research dollars on postdocs instead.

GSI positions are also crucial for support of graduate students, and even many students who eventually become GSRs start as GSIs. There is a real danger that our GSI positions for entering graduate students are ceasing to be attractive compared to peer institutions where the corresponding positions simply pay more for less work. Using short-term entry fellowships, with or without teaching, as investments to bring the best graduate students to Berkeley will help our graduate programs to continue to function at a high level. If we are to enable the recruiting of diverse cohorts of excellent graduate students, who will enable us to retain our competitiveness with peer institutions for grant money, a more relevant comparison in viewing compensation is to compare to science departments elsewhere rather than to other disciplines on campus. Berkeley pays astronomers on a different scale than, for example, economics faculty, because the market for stargazers is not the same as the market for economists. By the standard of peers, our graduate student compensation in science departments is ceasing to be competitive and challenging our recruitment of a diverse population.

Hence we recommend that the university should reinvigorate its previous push to increase the number of university graduate student fellowships in STEM fields via fundraising. In tandem, it should emphasize that producing STEM experts is a Berkeley priority, along with (currently more visible) priorities such as undergraduate access. Such an emphasis will broaden the pool of Californians who feel that they benefit from Berkeley's continued existence as an elite Ph.D.-granting institution. The smaller number of graduate fellowships available at Berkeley, in comparison to even second-tier private competitors, is already a key challenge to keeping our graduate programs competitive. Fellowships for research will help faculty to concentrate on curiosity-driven research and take risks, contributing to the development of competitive proposals for external funding. The precise mix of partial versus full research fellowships, versus entry supplements for students who may be GSIs, will vary between departments—as will the optimal implementation of campus finance reform.

Berkeley's graduate programs in the physical sciences built up their deserved reputation through decades of faculty effort and university support. It is dangerous to assume that these programs will maintain their reputation indefinitely if the university shifts its priorities elsewhere. Faculty will continue to do their part: they are working to find ways for GSIs to teach larger groups of students efficiently, including online, and faculty continue to bring in external funding that supports the vast majority of GSR positions. The best means of graduate program support should be determined by chairs and deans with input from faculty, but we hope that the central administration will do its part to make this possible and share successful practices.

Recommendation: Targeted fund-raising is rapidly increasing graduate student fellowship support in the physical sciences at our peer institutions, and it is crucial that Berkeley at least match this effort. Financial questions, such as how best to offer attractive GSI/GSR packages to students and whether the current approach to indirect costs is ideal for maintaining an effective research environment, were not a major subject of our retreat. However, these issues are clearly central to the success of physical sciences at Berkeley, and we recommend that this committee be consulted and allowed to offer an opinion on proposed financial changes of relevance to our graduate programs. Students who would contribute greatly to Berkeley will look elsewhere if current trends continue, and their choices are directly coupled to the infrastructure challenges below.

8 Building Research Infrastructure: Facilities, Tools, and People

Facilities and Tools: We have focused on new scientific goals for most of this report, but there are also changes in how we seek to answer them, both experimentally and theoretically. Berkeley is at risk of falling behind both in terms of buildings/facilities and the tools that they host. We wish to note at the outset that there are already challenges at the moment for faculty to obtain access to established tools, particularly for faculty whose work is not within the LBNL mission. As hinted at in Section 4, we are failing to meet our obligations to our faculty if we cannot at least offer them facilities comparable to those at other UCs (chiefly UCLA and UCSB, in that field); we would not accept such a situation with regard to our libraries, for example.

CACPS has formed an ad hoc subcommittee led by Prof. Maboudian to explore opportunities across campus for improved access to current and future experimental tools, as this will be a long-term process requiring significant changes. A particular opportunity is that many of the experimental tools we discuss are also relevant to areas of engineering. The next decade may be an ideal time to revitalize the applied physical sciences in the College of Engineering, as some buildings come up for replacement. Buildings are their own issue, with a well-defined campus process that we do not wish to criticize; we can point out that

Berkeley will cease to be attractive to students and funding agencies if the science buildings, the laboratories within them, and the tools that faculty have access to, are not competitive.

We were happy to learn that there has been attention paid in the past year to strategies for revitalizing faculty laboratories in MPS. A detailed list of emerging experimental tools would be rather technical and require broad input from faculty, and we would rather not appear to deprioritize tools omitted from a brief list. It is also a difficult question to determine the best way to share expensive tools and how to go out and seek funding for them. But any tour of the shared facilities at our private peers, followed by a tour of what is available on the Berkeley campus, will make some disparities clear; there have also been problems related to whether existing facilities reporting to one department/college are functioning well for others, but that may be improving. While CACPS members can advise on which shared experimental tools are most needed, it could be that questions about finances and buildings are sufficiently central that additional expertise should be brought in. Such a committee focused on the financial model for revitalizing Berkeley science infrastructure could perhaps operate jointly with the life sciences.

The advent of computational and statistical tools such as machine learning are having a dramatic effect across many areas of physical sciences. It will be exciting to see how the Division of Computing, Data Science, and Society grows, and there are enormous opportunities for mutually beneficial collaborations in both research and education. Finding an effective way to generate joint research projects, such as shared spaces, should be a high priority. Joint education we will leave to others, but we hope that departments will see campus's commitment to the new Division of Computing, Data Science, and Society, which is a rare case where Berkeley's investments are comparable to those of our private peers, as an opportunity to modernize education. The physical sciences provide a number of exciting applications for data science, such as the seismographic measurements in Section 3; the current importance of data science is also an example of how discoveries in the mathematical sciences such as statistics can have far-reaching consequences, and why we should ensure that such discoveries continue.

Recommendation: Emerging physical scientists will choose universities that can offer the tools and other infrastructure necessary to pursue the frontiers of knowledge. Our campus infrastructure, including both research laboratories and experimental equipment, is currently insufficient to sustain our excellence in the physical sciences. We recommend that a subcommittee of this committee be formed to advise campus leadership on establishing priorities for improving campus access to essential experimental tools and for modernizing campus infrastructure for physical sciences. That committee may also wish to consider cost recovery and other funding sources to enable those investments.

Administrative Infrastructure: In the preceding sections of this report, we discussed several grand challenges in science, which often require grand, collaborative efforts ("big science"). One common thread in our discussions of those challenges was the need for centers and other groupings, and below we discuss how effective groupings can be fostered. However, Berkeley also excels in sole practitioner and small-group science, which may be "small science" in its cost but not in its ambition. The way most mathematicians and theoretical physicists carry out curiosity-driven research, often as individuals or in small groups, would be quite familiar to a philosopher or historian. To pick just one example, Ian Agol recently received the most lucrative prize in mathematics for solving a long-standing problem in topology; how to enable that kind of faculty research is our first topic.

Both kinds of science suffer when faculty are not able to devote sufficient time to research and student mentoring, and we agree with the Committee on the Future of Biology's recommendation to focus administrative spending in order to protect faculty time for research and education. One of the most efficient ways to improve the research of our faculty members, and to allow them to follow their curiosity, is to increase the time they actually have available for research. An obstacle to research is what faculty perceive as an increasing load of administrative tasks related to teaching, grant submission and monitoring, and other key functions. Given the huge increase in the student population in the physical sciences, many classes have doubled in size. Even if the teaching hours per week have not increased, the amount of work dedicated to run those classes has increased enormously (in tasks like answering emails, supervising GSIs, addressing student questions in office hours, mentoring students, managing arrangements for disabled students, providing letters of recommendation, etc.). For other administrative tasks, the workload of departmental staff has been increasing, which leads to faculty having to assume more administrative tasks outside their expertise as a stopgap.

On top of affecting the research of existing faculty, these issues make Berkeley less competitive to top researchers, which is having an effect on faculty searches. Conversely, at the same time as faculty wind up carrying out tasks that were previously the province of departmental staff, the role of non-faculty staff in important decisions such as faculty hiring is increasing. Just as recommended by the Chancellor's Advisory Committee on Biology, we encourage the university to maintain clarity about which tasks are efficiently done by faculty and which are not. It should be pointed out that there are some operational improvements, as in the processing of travel and other personal reimbursements, but it can feel like every improvement is counterbalanced by a new form or procedure, and that campus leadership is not taking account of the impact of procedural changes on faculty time.

Recommendation: We concur with the concern expressed in a recent life sciences report that business functions are soaking up an increasing amount of faculty time. Improvements would benefit both large collaborations and smaller efforts, and Berkeley needs to foster an environment in which faculty can pursue the directions most interesting to them. An efficient administrative infrastructure should free up faculty time to teach, mentor students, and pursue new directions that may become the major scientific initiatives of tomorrow.

Creating and Renewing Research Partnerships: An important aspect of VCRO's mission is to aid faculty in the development of large-scale center proposals, which attract an increasing share of federal funding. Berkeley has seen some notable successes in this area in 2020. Organizing centers can also be important in presenting an attractive front for private funding. Beyond just a means to get money, successful partnerships make a real difference in faculty success, and that holds true whether partnership means a closely linked collaboration on a single experiment or an umbrella helping many different individuals or subgroups to prosper.

Like all collective human endeavors, forming partnerships can be a complex enterprise. Any scientist can confirm that many disagreements in science are not about correctness but about importance. Questions of which topics are most important, either in absolute terms or for a particular funding source, naturally arise in forming partnerships for limited-submission proposals, and, less often, questions about who is best placed to articulate that importance. We have two ideas for how this complex process might be helped along, but these are minor tweaks to a process that already works well given the finite resources available.

When an area of science is emerging, or a potential call for funding is just visible on the horizon, we think it would be useful to have a one-day internal interdepartmental workshop where interested faculty could learn about the field and how to organize it. Obviously some faculty time would be needed to get the workshop off the ground, but it might be advantageous to involve postdocs as well. The involvement of the Miller Foundation could be very helpful given its experience with symposia and its mission to support the physical sciences across campus. Perhaps multiple center concepts could be presented and discussed constructively at such a meeting, depending on the timing of funding calls. The point is to encourage faculty to self-organize, rather than imposing a particular structure or leadership at the very beginning, and to find the right mix of what we want to do and what agencies or donors want to support. We think several of the topical areas earlier in this report could be appropriate subjects for such workshops.

Obviously hard decisions will remain for VCRO. VCRO's budget is not unlimited and for the most part has to be spent on "investment" (i.e., spending that will generate future grants) rather than "consumption" (i.e., doing science). Most federal grants have a single lead PI. To the extent that some of those hard decisions about spending and proposal leadership can be seen to come from collective faculty input, it may help in getting faculty to buy in and commit their time not just as leaders of centers but as participants who contribute actively even to the less glamorous aspects. Indeed, finding the right incentives for faculty to go out and raise grant revenue is a continuing challenge, related to the time shortages mentioned earlier.

A less concrete suggestion is to think about the life cycle of centers and how they are renewed–a "circular economy" for centers, maybe. Science changes, and personnel change, but when Berkeley creates a center, there may not be enough thought given to long-term planning. It might make more sense for Berkeley to have fewer centers but make sure that they are worthy of the term "center", in the sense of being the origin of a web of shared interests. There are of course many examples where centers and other VCRO operations have successfully reinvented themselves, and it would be nice to encourage that process broadly. One possibility, similar to how some programs have worked at the Simons Institute, is to have a broad umbrella to define a center, with the idea that the umbrella definition has a degree of permanence, but then to develop themes of a few years' duration under that umbrella. We hope that this section will start a continuing conversation about research partnerships, and we were happy to learn that the suggestion above of one-day workshops may be implemented rapidly. We believe that faculty in the physical sciences will be willing to engage in this and other ways to use their technical expertise to further University goals.

Recommendation: Understanding that faculty are frequently overcommitted, it can be challenging to devote the time and energy needed to organize groups of colleagues around large-scale multidisciplinary (and often multi-institutional) funding opportunities. We recommend that campus provide support for workshops that will galvanize our research community in potential priority areas of the physical sciences, including those enumerated above. These will facilitate our institutional response to large funding opportunities by allowing teams to develop organically and inclusively, while also benefiting individual research efforts. Support could also take the form of seed grants to encourage faculty to engage in new directions and/or strategic areas in the physical sciences.

Chancellor's Advisory Committee on Physical Sciences

Richard Allen, Earth and Planetary Science
Steve Beckwith, Astronomy; Space Sciences Laboratory
Kristie Boering, Chemistry; Earth and Planetary Science
Phill Geissler, Chemistry
Dan Kasen, Astronomy; Physics
Alessandra Lanzara, Physics
Jeff Long, Chemistry; Chemical and Biomolecular Engineering (co-chair)
Chung-Pei Ma, Astronomy
Roya Maboudian, Chemical and Biomolecular Engineering
Antonio Montalban, Mathematics
Joel Moore, Physics (co-chair)
Peidong Yang, Chemistry

Staff Liaisons

Tiff Dressen, Office of the Vice Chancellor for Research
Colette Patt, Assistant Dean, Division of Mathematical & Physical Sciences

A Appendix: CACPS timeline, retreat participation, and charge

CACPS solicited input for the report from physical sciences faculty via brief presentations at faculty meetings of individual departments and a one-day retreat on May 8, 2019, convened by Vice Chancellor for Research Randy Katz. The opinions in this report represent only the membership of CACPS, whose terms are envisioned to last either two to three years.

Retreat participants in addition to members of CACPS:
Carlos Bustamante, MCB; Physics; Chemistry
Michelle Chang, Chemistry
Imke de Pater, Astronomy; EPS
Craig Evans, Mathematics
Teresa Head-Gordon, Chemistry; Bioengineering; CBE
Jeffrey Neaton, Physics; Associate Laboratory Director, LBNL
Deborah Nolan, Statistics
Kristin Persson, MSE
Michael Witherell, Physics; Director, LBNL

Staff presenter:
Andrew Eppig, Division of Equity and Inclusion

Retreat organization was coordinated by Verna Bowie of the Office of the Vice Chancellor for Research. Facilities were provided by the Space Sciences Laboratory.

Acronyms:
CBE = Chemical and Biomolecular Engineering
EPS = Earth and Planetary Science
LBNL = Lawrence Berkeley National Laboratory
MCB = Molecular and Cell Biology
MSE = Materials Science and Engineering

CACPS charge (following page)

Charge for the Chancellor's Advisory Committee on Physical Sciences (CACPS)

March 2019

The Chancellor's Advisory Committee on Physical Sciences (CACPS) is being established in 2019 to enable a coordinated approach to providing faculty insight and input to campus leadership on opportunities for Berkeley to excel in scholarship and research across the physical sciences, and to ensure a diverse faculty.

In consultation with the cognizant Deans, department Chairs and faculty, the CACPS will provide the Chancellor, Executive Vice Chancellor and Provost, Vice Chancellor for Research, and cognizant Deans with insight into campus and external trends occurring within the physical sciences, as well as advice and recommendations about opportunities and challenges, strategies and benefits, and choices that UC Berkeley should consider related to the relevant broad field. The Committee is encouraged to select and focus on a short list of topics at at time; these can evolve over time but should lead to periodic sets of recommendations. Areas can include:

- New areas of research and new faculty expertise needed for UC Berkeley to remain at the forefront of the broad field.
- Recruitment and retention strategies to effectively support and enhance faculty diversity.
- Priorities among, and the resources and strategies needed to maintain, present areas of strength and development of new ones.
- The ongoing review of the quality of teaching and of research.
- The evaluation of teaching programs in the relevant fields.
- Ways to productively align with UC Berkeley's Strategic Plan and priorities[1];
- Ways to strengthen coordination, cooperation, and collaboration within the broad field on campus.[2]
- Ways to strengthen connections with other fields of scholarship and research across the campus.
- Other issues of import to the campus' contributions and impact in the field.

CACPS members are asked to serve terms of 2-3 years.

To ensure regular exchange of ideas, members are asked to bring the work of the Committee to the attention of their colleagues at regular faculty meetings, both to disseminate information and to solicit input.

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[1] In 2019 these include the Data Science, the Brain Initiative, the Innovative Genomics Institute, and the six campuswide Signature Initiatives.

[2] For the Chancellor's Advisory Council on Biology (CACB), a precursor to the CACPS and a new CAC on Life Sciences, this included the coordination of teaching programs in the relevant fields, reviewing FTE requests from departments and advertisements for faculty positions, and nominating search committee members for consideration by the appropriate deans.