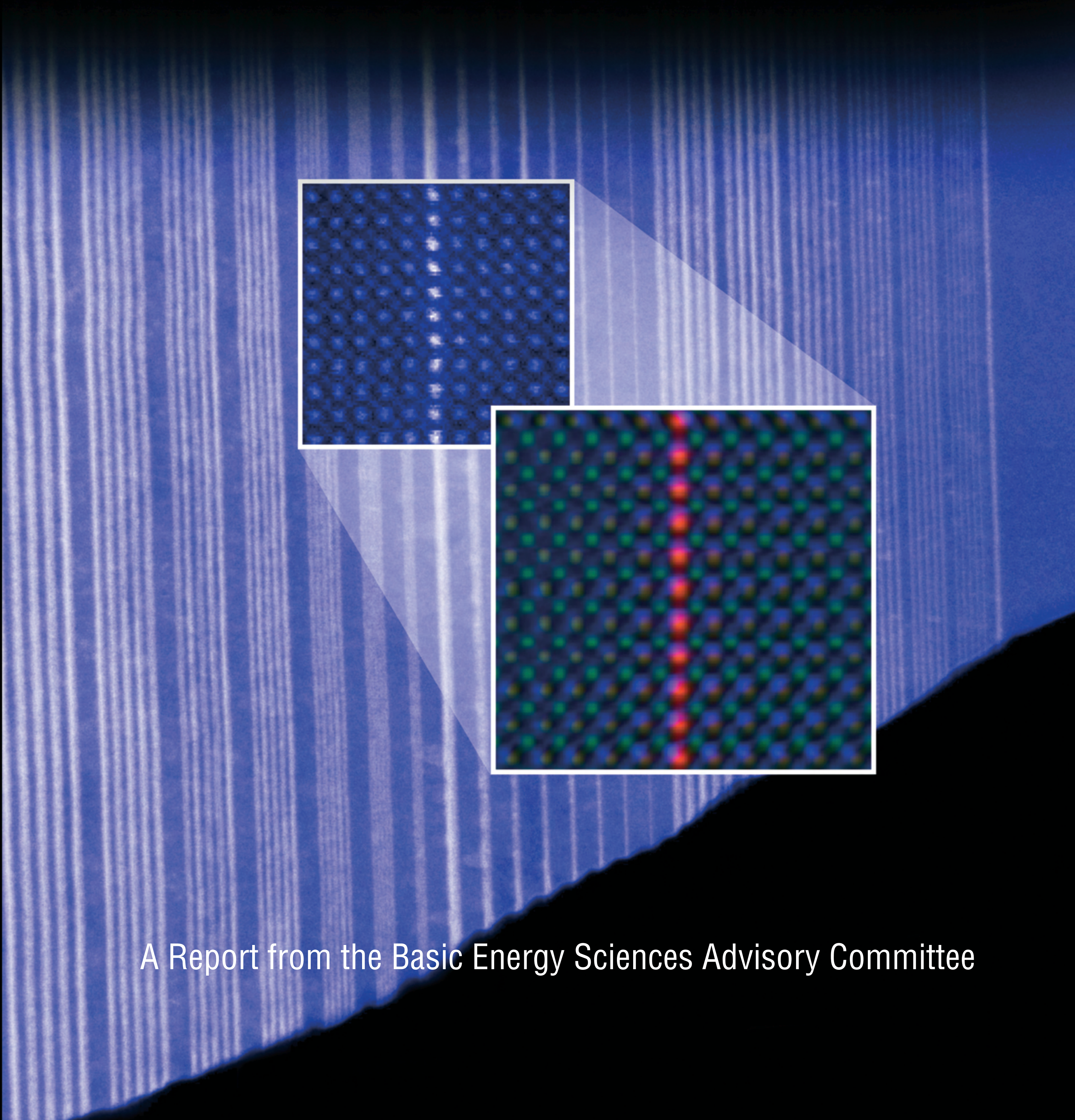
Directing Matter and Energy: Five Challenges for Science and the Imagination



A Report from the Basic Energy Sciences Advisory Committee

Directing Matter and Energy: Five Challenges for Science and the Imagination

A Report from the
Basic Energy Sciences Advisory Committee

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GRAND CHALLENGES FOR BASIC ENERGY SCIENCES

It is frequently said that any sufficiently advanced technology is indistinguishable from magic. Modern science stands at the beginning of what might seem by today's standards to be an almost magical leap forward in our understanding and control of matter, energy, and information at the molecular and atomic levels. Atoms—and the molecules they form through the sharing or exchanging of electrons—are the building blocks of the biological and non-biological materials that make up the world around us. In the 20th century, scientists continually improved their ability to observe and understand the interactions among atoms and molecules that determine material properties and processes. Now, scientists are positioned to begin directing those interactions and controlling the outcomes on a molecule-by-molecule and atom-by-atom basis, or even at the level of electrons. Long the staple of science-fiction novels and films, the ability to direct and control matter at the quantum, atomic, and molecular levels creates enormous opportunities across a wide spectrum of critical technologies. This ability will help us meet some of humanity's greatest needs, including the need for abundant, clean, and cheap energy. However, generating, storing, and distributing adequate and sustainable energy to the nation and the world will require a sea change in our ability to control matter and energy.

One of the most spectacular technological advances in the 20th century took place in the field of information, as computers and microchips became ubiquitous in our society. Vacuum tubes were replaced with transistors and, in accordance with Moore's Law (named for Intel co-founder Gordon Moore), the number of transistors on a microchip has doubled approximately every two years for the past two decades. However, if the time comes when integrated circuits can be fabricated at the molecular or nanoscale level, the limits of Moore's Law will be far surpassed. A supercomputer based on nanochips would comfortably fit in the palm of your hand and use less electricity than a cottage. All the information stored in the Library of Congress could be contained in a memory the size of a sugar cube. Ultimately, if computations can be carried out at the atomic or sub-nanoscale levels, today's most powerful microtechnology will seem as antiquated and slow as an abacus.

For the future, imagine a clean, cheap, and virtually unlimited supply of electrical power from solar-energy systems modeled on the photosynthetic processes utilized by green plants, and power lines that could transmit this electricity from the deserts of the Southwest to the Eastern Seaboard at nearly 100-percent efficiency. Imagine information and communications systems based on light rather than electrons that could predict when and where hurricanes make landfall, along with self-repairing materials that could survive those hurricanes. Imagine synthetic materials fully compatible and able to communicate with biological materials. This is speculative to be sure, but not so very far beyond the scope of possibilities.

Acquiring the ability to direct and control matter all the way down to molecular, atomic, and electronic levels will require fundamental new knowledge in several critical areas. This report was commissioned to define those knowledge areas and the opportunities that lie beyond. Five interconnected Grand Challenges that will pave the way to a science of control are identified in the regime of science roughly defined by the Basic Energy Science portfolio, and recommendations are presented for what must be done to meet them.

FIVE GRAND CHALLENGES FOR BASIC ENERGY SCIENCES

- *How do we control material processes at the level of electrons?*

  Electrons are the negatively charged subatomic particles whose dynamics determine materials properties and direct chemical, electrical, magnetic, and physical processes. If we can learn to direct and control material processes at the level of electrons, where the strange laws of quantum mechanics rule, it should pave the way for artificial photosynthesis and other highly efficient energy technologies, and could revolutionize computer technologies.

- *How do we design and perfect atom- and energy-efficient synthesis of revolutionary new forms of matter with tailored properties?*

  Humans, through trial and error experiments or through lucky accidents, have been able to make only a tiny fraction of all the materials that are theoretically possible. If we can learn to design and create new materials with tailored properties, it could lead to low-cost photovoltaics, self-repairing and self-regulating devices, integrated photonic (light-based) technologies, and nano-sized electronic and mechanical devices.

- *How do remarkable properties of matter emerge from complex correlations of the atomic or electronic constituents and how can we control these properties?*

  Emergent phenomena, in which a complex outcome emerges from the correlated interactions of many simple constituents, can be widely seen in nature, as in the interactions of neurons in the human brain that result in the mind, the freezing of water, or the giant magneto-resistance behavior that powers disk drives. If we can learn the fundamental rules of correlations and emergence and then learn how to control them, we could produce, among many possibilities, an entirely new generation of materials that supersede present-day semiconductors and superconductors.

- *How can we master energy and information on the nanoscale to create new technologies with capabilities rivaling those of living things?*

  Biology is nature's version of nanotechnology, though the capabilities of biological systems can exceed those of human technologies by a vast margin. If we can understand biological functions and harness nanotechnologies with capabilities as effective as those of biological systems, it should clear the way towards profound advances in a great many scientific fields, including energy and information technologies.

- *How do we characterize and control matter away— especially very far away —from equilibrium?*

  All natural and most human-induced phenomena occur in systems that are away from the equilibrium in which the system would not change with time. If we can understand system effects that take place away—especially very far away—from equilibrium and learn to control them, it could yield dramatic new energy-capture and energy-storage technologies, greatly improve our predictions for molecular-level electronics, and enable new mitigation strategies for environmental damage.

We now stand at the brink of a "Control Age" that could spark revolutionary changes in how we inhabit our planet, paving the way to a bright and sustainable future for us all. But answering the call of the five Grand Challenges for Basic Energy Science will require that we change our fundamental understanding of how nature works. This will necessitate a three-fold attack: new approaches to training and funding, development of instruments more precise and flexible than those used up to now for observational science, and creation of new theories and concepts beyond those we currently possess. The difficulties involved in this change of our understanding are huge, but the rewards for success should be extraordinary. If we succeed in meeting these five Grand Challenges, our ability to direct and control matter might one day be measured only by the limits of human imagination.