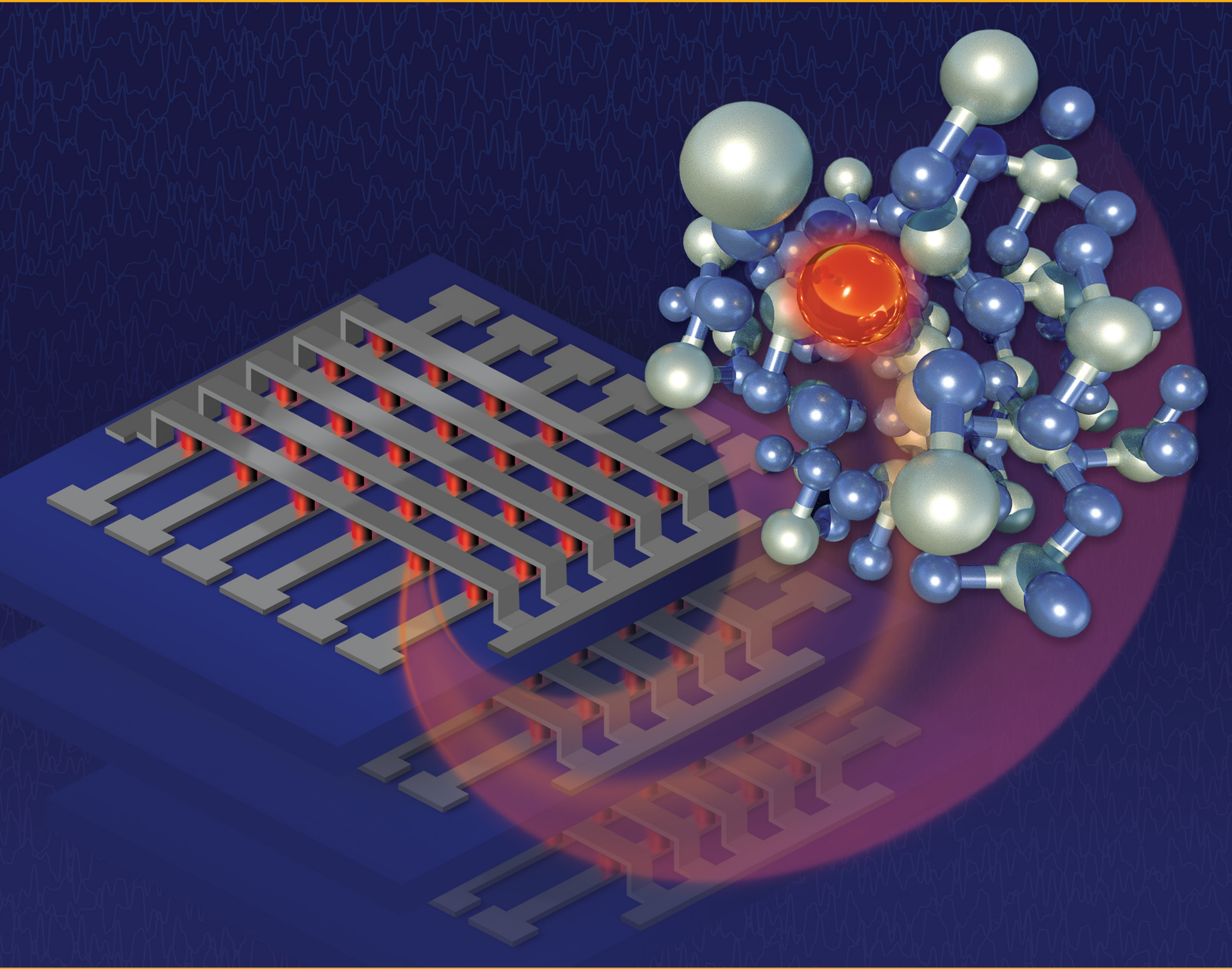
Basic Research Needs for
Microelectronics



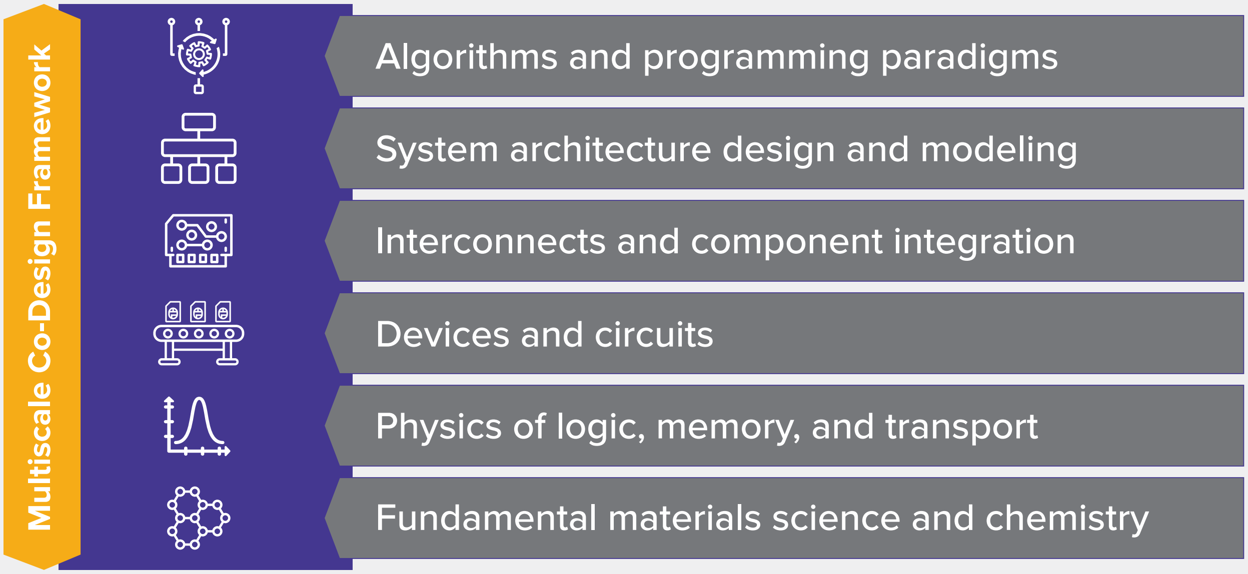
Discovery science to revolutionize microelectronics beyond today's roadmaps

Blazing a trail to compact, efficient, high-performance computers and a modernized electricity grid

Since the invention of the integrated circuit in 1958, advances in microelectronics have followed Moore's law and other scaling laws. These have led to over a billion-fold increase in the number of transistors on a chip.

The Department of Energy's Office of Science (DOE-SC) programs have always been at the cutting edge of microelectronics, making major contributions to the scientific understanding, materials, and advanced instrumentation that enabled innovations to promote scaling. This has driven transformative advances in microelectronics for the challenging demands of DOE's high performance computing and science facilities. Now, strong evidence exists that scaling is approaching its physical and economic limits, and yet, the growth of data-centric computing and sensor networks is redefining computing workloads and microelectronics needs. In addition, greatly improved microelectronics are needed for the nation's electricity grid if it is to be energy-efficient, resilient to natural phenomena and intentional attack, and agile in adapting to fluctuations in demand and power generation. Sustained and rapid progress in microelectronics science and technology from millivolt to megavolt scales is thus essential if we are to continue pushing the boundaries of science within DOE, and more significantly, to continue to lead the global information and power technology revolution.

In October 2018, DOE-SC convened a workshop to address Basic Research Needs for Microelectronics by a "co-design" approach (see below). Participants focused on scientific issues associated with advanced microelectronics technologies for applications relevant to the DOE mission, including computing, power grid management, and science facility workloads. (Topics of direct relevance to quantum information science and quantum computing were outside the scope of this workshop.) The workshop was organized around microelectronics needs for three areas: 1) future DOE-SC facilities, 2) high performance computing beyond exascale (a billion billion calculations per second), and 3) power control, conversion, and detection for a modernized electrical grid and related high power applications. Panels were formed around each of these areas, with a fourth panel formed to address Crosscutting Research. Workshop participants were asked to focus on a co-design innovation ecosystem in which materials, chemistries, devices, systems, architectures, algorithms, and software are researched and developed in a closely integrated fashion, with feedback and interdisciplinary collaboration at each interface in this microelectronics technology hierarchy. The panels identified the five Priority Research Directions on the following page. The full workshop report will be available at https://science.energy.gov/bes/community-resources/reports.



Co-design involves multi-disciplinary collaboration that takes into account the interdependencies among materials discovery, device physics, architectures, and the software stack for developing information processing systems of the future. Such systems will address future DOE needs in computing, power grid management, and science facility workloads.

Priority Research Directions

- **Flip the current paradigm: Define innovative material, device, and architecture requirements driven by applications, algorithms, and software**

  Key Questions: *How can we optimize and integrate across physical, logical, and communication and control hierarchies? How will system-level optimization enable directed materials/device discovery and innovation?*

  Materials properties, microelectronic devices, architectures, and algorithms must be understood and designed from the atomistic to the systems level to address the critical technical challenges facing DOE in its missions of science, energy, and national security. The outcome of an "end-to-end co-design framework" will reshape high performance computing, data analytics, the electricity grid, and other computing intensive and high power applications.

- **Revolutionize memory and data storage**

  Key Questions: *How do we link physics, materials, architectures, and algorithms to overcome current physical limits on access and retention times for memory and storage? What innovations will minimize data movement and reduce energy consumption by orders of magnitude?*

  Memory technologies are critically important in all aspects of data acquisition, analysis, and storage, and have the potential to perform efficient computations within, or proximally close to, the memory element. We face fundamental tradeoffs between fast memory access, capacity, and data retention time, as well as key challenges in energy usage and heat dissipation. Meeting these challenges will require coordinated breakthroughs in materials, device design, computer architecture, and algorithms.

- **Reimagine information flow unconstrained by interconnects**

  Key Questions: *How can we minimize data movement while maximizing information transfer? What novel electronic/optical states of matter can be discovered and manipulated to design non-traditional interconnects at the atomic, micro, and macro scales?*

  A co-design approach to developing novel interconnect architectures will enable seamless integration of large-scale, real-time computation with communications and sensing to dramatically improve data transfer rates, connectivity, and reconfigurability.

- **Redefine computing by leveraging unexploited physical phenomena**

  Key Questions: *What unexplored materials, phenomena, or alternative computing models could perform computation far more efficiently than today's technology? How will these new systems be modeled and programmed?*

  The capabilities of the prevailing model of computation, the von Neumann model, are increasingly constrained by the energy inefficiency of established hardware and architecture. Understanding and using new computing models based on unexploited phenomena require a co-design approach spanning architectures and algorithms to physics, materials science, and new devices.

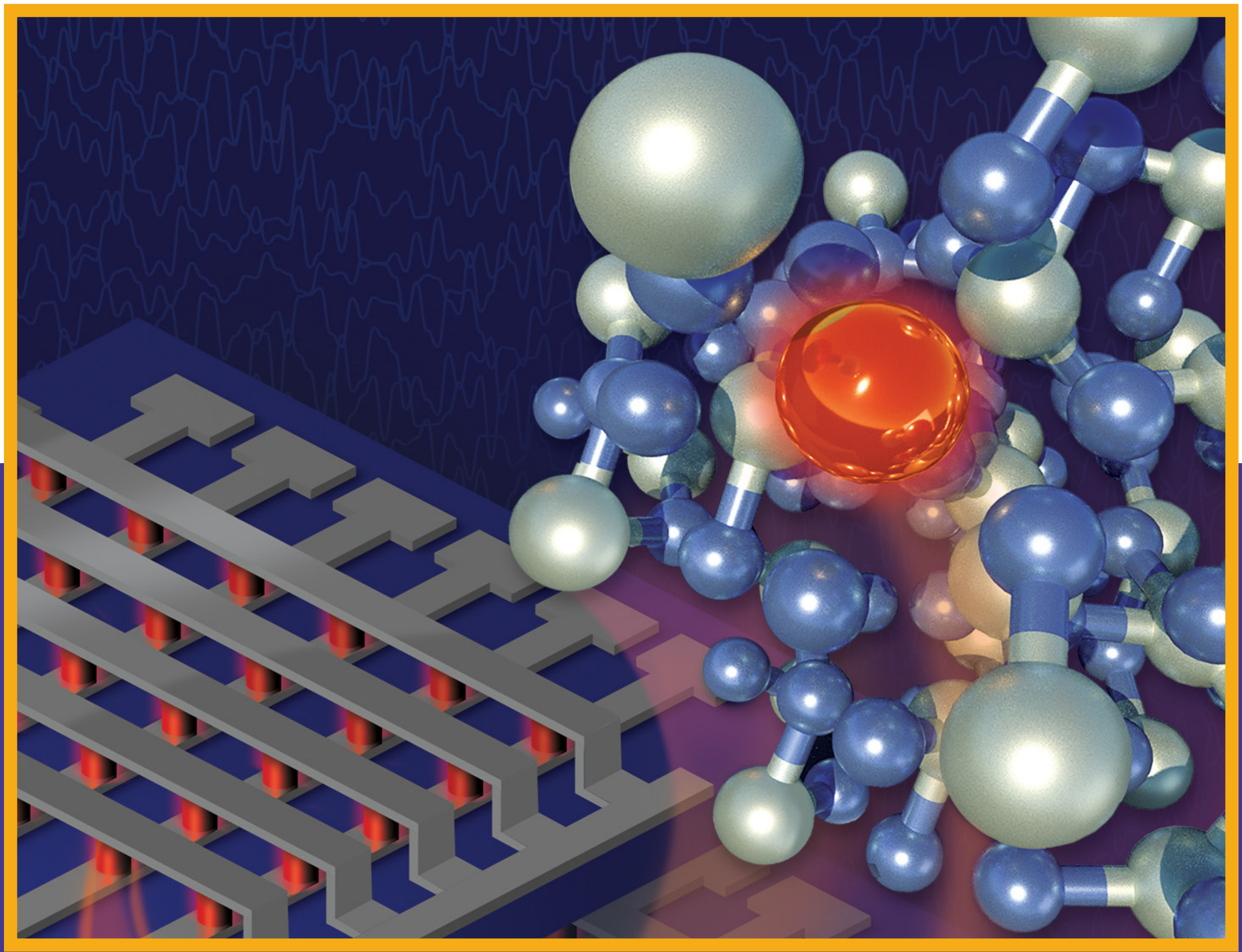
- **Reinvent the electricity grid through new materials, devices, and architectures**

  Key Question: *Using a co-design approach, how do we create novel devices based on new materials to enable revolutionary breakthroughs in the performance, reliability, and security of power conversion systems?*

  Revolutionary advances in power electronics for the electricity grid will require the design, synthesis, understanding, processing, and integration of advanced semiconductors and magnetic and dielectric materials. Novel device, circuit, and thermal transport concepts will be developed to exploit the unique physical properties of these materials. Such energy-efficient power conversion systems are necessary to replace the century-old electricity grid with one appropriate for the 21st century. They could also be applicable to electric transportation and use in extreme environments such as accelerators and power generation facilities.

Summary

In the future, computing systems encompassing new materials, devices, architectures, algorithms, and software will be needed to maintain the continued upward trajectory in performance that Moore's law scaling has historically provided. Optimization must occur at every level of computing and power microelectronics systems, and co-design principles will be essential if we are to deploy systems that meet the future needs of DOE-SC and the nation. Among the challenges is discovery science that can lead to microelectronics for exascale computers and beyond with a small footprint and low power utilization. Such high performance computation will be necessary for analyzing and managing the vast amount of data that will be generated by future DOE-SC facilities to enable new discoveries. Furthermore, advances in new microelectronics materials, and their integration within a co-design framework, are required to transform power electronics and the electricity grid into a modern, agile, resilient, and energy-efficient system.



Cover image: A simplified schematic of a cross-bar circuit element designed for future low power, non-volatile memory or neuromorphic computing applications. "Row" and "column" metal interconnects form the cross-bar structure, with nanoscale memory elements residing at the intersections. Current research is focused on the design of these materials at the atomic level to enable dense digital and analog memory arrays with performance characteristics well beyond today's circuits.

Image courtesy of Argonne National Laboratory.

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