Science and Engineering Beyond Moore's Law (SEBML)

Computation stands on physical foundations that have changed multiple times, progressing from mechanical, to electro-mechanical, to electronic systems embodied in vacuum tubes and then transistors. This evolution has been foundational to science, and each epoch overlapped the previous computing paradigm as new technology moved from the laboratory to practicality. We are nearing the scalability limits of the silicon transistor, creating an urgent need for a new basis for computing. We cannot specify the next generation precisely, but creating it will require a sustained effort in new materials, new computer architectures and algorithms, new state variables, and the utilization of classical and intrinsically Quantum phenomena.

The technological foundations of prosperity in the past century were the internal combustion engine and the transistor. A century ago, the internal combustion engine created a revolution in the processing and distribution of goods, and fifty years later the transistor did the same for information. Both devices were amenable to successive generations of engineering refinement; both become cheap and ubiquitous; both now face looming fundamental limitations. These inventions harvested the fruits of earlier basic scientific research in Thermodynamics and Quantum Mechanics, and continue to define the shape of global society today. Basic research now underway points toward similar advances that could lead to another century of prosperity. The purpose of the initiative on Science and Engineering Beyond Moore's Law (SEBML) is to consider these issues in the realm of information processing and distribution.

The transistor was demonstrated in 1947, and once multiple devices were simultaneously fabricated, the packing density of devices on a chip began to increase. Moore's Law is the empirical observation, made in 1965, by the co-founder of Intel, Gordon E. Moore, that semiconductor device density, and therefore computer processing power, doubles about every 18 months. Currently, many innovations are being pursued to prolong the scalability of computer processing power, but with silicon technology the fundamental physical and conceptual limits of Moore's Law are likely to be reached in 10 to 20 years. The same law applies to the information the hardware is designed to store (memory) and process (computation). This has revolutionized science and technology opening new avenues for data driven research, Materials By Design, and other important areas of future growth in the vision of MPS.

SEBML aims to advance the forefront of communications and computation capability beyond the physical and conceptual limitations of current technologies. To take computing and communications *beyond* Moore's Law will require entirely new scientific, engineering, and conceptual frameworks, both for computing machines and for the algorithms and software that will run on them. NSF will approach the realization of these demands through a range of investigations in the following three areas of emphasis: (1) the basic science that underpins the hardware and software that are the tools of communications and computation; (2) the engineering principles that drive the design of these tools; and (3) the computational framework that governs their utilization.

One aspect of SEBML research will retain the classical computing paradigm of the fast logic switch, currently implemented through transistors, but will focus on exploring new materials and devices to replace transistors and combining that with new architectures that overcome current limitations on the speed and energy efficiency of classical binary switching. At the same time SEBML research will explore the entirely new science that emerges when the sizes of systems reach the limit in which quantum mechanics dominates the behavior, thus rendering the classical computing paradigm invalid.

Programs in the MPS Divisions of Materials Research, Physics and Chemistry are positioned to address the fundamental research identifying new phenomena and new materials that could replace current hardware. Programs in the MPS Division of Mathematics focus on fundamental new mathematical principles that can form the basis of new algorithms and new approximation tools. Programs in all four MPS Divisions contribute to the emerging field of Quantum Information Science (QIS), which incorporates the concepts of *entanglement* and *superposition* to define a completely new computing paradigm rather than simply constructing a faster or parallel implementation of a classical binary switch.

Programs in the ENG Division of Electrical, Communications, and Cyber Systems (ECCS) are positioned to support research on new device concepts in photonics, nanoscience, spintronics, and molecular-based approaches that might replace the transistor switch as the physical basis of computing. Programs in ECCS also explore the role that quantum phenomena will play in the design and construction of new devices that make up computer hardware.

Programs in the CISE Division of Computing and Communications Foundations (CCF) are positioned to explore information concepts that can lead to new computing architectures and new algorithms, programming models and languages, and systems software that capitalize on and extend the power of the binary switch. Programs in CCF also include the fundamentals of information science that contribute to the field of QIS, which arises from the union of information science with quantum mechanics, as well as other possible computing paradigms.

The Office of Cyberinfrastructure (OCI) will partner with these three Directorates in pursuit of infrastructure and computational needs that support all of the research activities. OCI will also develop applications that could take advantage of the unique architecture and approaches as well as working on integration issues associated with making SEMBL capabilities part of the larger cyberinfrastructure framework to support science and engineering.

It is anticipated that all Directorates involved in SEBML will engage in joint efforts to address the three basic areas of emphasis, as an integrated approach that cuts across disciplines is needed to foster the rapid development that is needed to maintain US leadership in this area. The Directorates have in place proven connections within the Foundation that serve to bring research communities together, as demonstrated through their collective efforts in the National Nanotechnology Initiative (NNI), Information Technology research (ITR), Nanoelectronics for 2020 and Beyond (NEB), and Cyber-Enabled Discovery and Innovation (CDI). There also close interactions with other governmental funding organizations, as demonstrated through programs that overlap with the DoE and the DoD, NIST, and with industry, as demonstrated by the recent supplements to Nanoscale Science and Engineering centers awarded in collaboration with the Nanoelectronics Research Corporation, and with international collaborators. Through its focus on the integration of research and education, and support provided primarily to universities, the NSF approach also serves to prepare the workforce needed to implement new technologies as they become available.

The scope of SEBML is intrinsically broad, and will require implementation that utilizes existing NSF programs, as noted above, and the creation of new, sustained efforts that engage all the expertise required for the problem. The new solicitation, "Nanoelectronics for 2020 and Beyond" indicates initial pathways for this work, supporting investigators at a small group level, with engagement across traditional departmental areas. Addition of Quantum Information studies and sustainable group or center level awards could establish SEBML in a large scientific community and create university investment that would stimulate hiring and create career paths in the area.

The combined development of new concepts for information management and for physical approaches that supersede standard electronic devices will have enormous societal impact. SEBML has an immediate and direct impact on the national economy, as the development of new approaches is critical to sustaining U.S. leadership and competitiveness in the global semiconductor industry. SEBML also indirectly impacts energy and climate, as faster and more sophisticated computational tools are needed to model complex systems and to extract knowledge from massive data sets. Finally, SEBML directly addresses national security needs via insight into, and possibly diversion of, threats posed by the potential of quantum algorithms to render current security systems ineffective.

This emerging NSF activity builds on the past ten years of support for the NNI priority area. Out of that period has come a broad spectrum of tools and techniques that allow us to study and utilize nanoscale systems. This has enabled discoveries in new materials and new devices and has led to extensive applications in areas from biology to materials science. While SEBML has roots in NNI, the goals of SEBML go beyond NNI, to examine those concepts and paradigms that are not size-dependent and are scalable below the roughly ten-nanometer lower limit addressed by NNI funding. Some of the concepts envisioned in SEBML may not even function at a length scale above ten nanometers. This is a critical juncture for an enhanced investment in SEBML, which will capitalize on these earlier investments in NNI while also pushing technology beyond the scaling limits of silicon technologies and into the quantum limit.