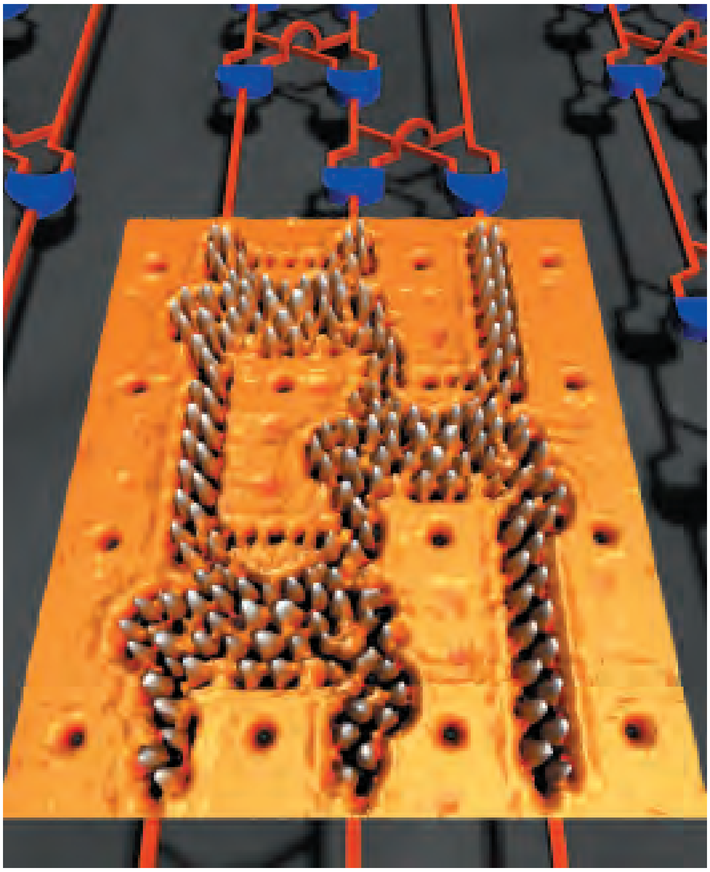
How IBM Sustains the Leading Edge

At IBM Research, we define innovation as more than mere discovery and invention. True innovation only occurs when new ideas enter the marketplace and make a difference for society.

Although we constantly focus on the market, IBM Research has also produced a remarkable string of scientific firsts in physics and in other fields of science and engineering. In large part, it is our focus on the marketplace that has sparked excellence in our science. This is amply illustrated by our history, which stretches back more than a century to Herman Hollerith and his early mechanical tabulators. A 1911 merger of Hollerith's Tabulating Machine Company and two other companies resulted in the formation of the Computing-Tabulating-Recording Co., renamed International Business Machines Corp. in 1924.

Talents for mechanical design rather than formal academic training characterized the innovators of the early mechanical and later electromechanical machines. IBM hired its first doctorate-level employee in 1945, when Wallace J. Eckert, an astronomer and pioneer of punched-card computation for scientific purposes, joined the company as director of the pure science department. His arrival strengthened an already established tradition of support for, and interest in, theoretical and computational science—a tradition that continues today.



Don Eigler, IBM Almaden Research Center

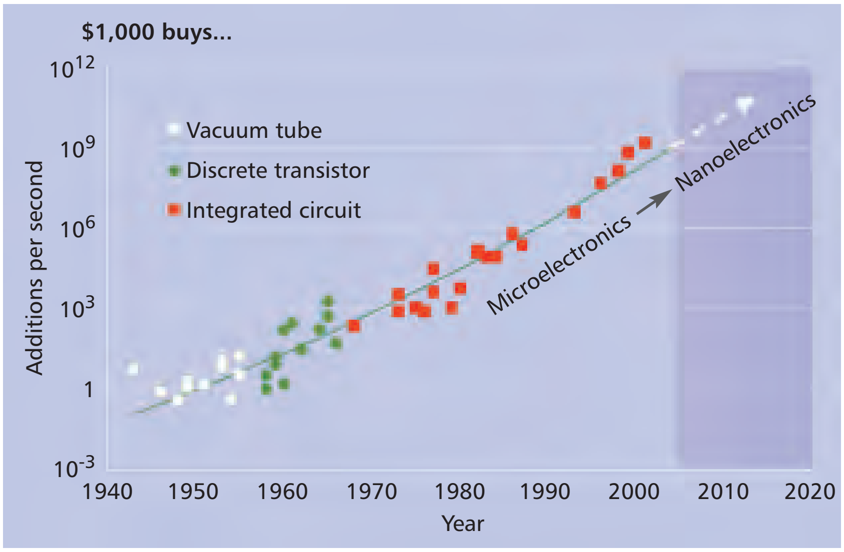
Figure 1. Scanning-tunneling microscope image of a three-input sorter logic circuit built from carbon monoxide molecules placed on a metal surface. This demonstration of "molecular-cascade logic" suggests the possibility of extremely small information-processing systems based on molecular dynamics.

Early advances

In the late 1940s, IBM and its competitors rapidly capitalized on wartime advances in electronics. As the first electronic calculators evolved into general-purpose computers, physicists and electrical engineers increasingly drove innovation. Commercial vacuum tubes proved too unreliable for computation, a challenge that motivated the development of clean-room fabrication techniques and, arguably, laid the basis for IBM's eventual entry into semiconductor manufacturing in 1959, the year the company introduced the world's first automated transistor manufacturing line. To match the speed of electronics, IBM developed fast random-access memories (RAMs), which were based on ferrite cores. The development in the 1940s of technology to store large quantities of data on magnetic drums, and then on magnetic disks in the 1950s, eventually led to the 1956 announcement of the first hard-disk drive—the random-access method of accounting and control (RAMAC) storage system.

These developments helped ignite the explosive growth in performance and the plummeting cost of computing, which continue to this day. The long-term trend of ever-decreasing costs of computation (Figure 2) has been fueled by relentless innovation at all levels—from materials and devices to circuit design, architectural organization, and manufacturing processes. Throughout this period, IBM Research developed and maintained a strong focus on the physics of the devices that process, store, and communicate information, as well as the materials and processes needed to fabricate those devices.

In transistor technology, notable innovations by IBM scientists included the single-transistor dynamic random-access memory (DRAM); the discovery and application of physical laws for transistor scaling; and advances in manufacturing processes such as projection lithography, the use of excimer lasers for lithography, chemically amplified photoresists, chemical–mechanical planarization, low-temperature epitaxy of silicon–germanium-alloy semiconductors, silicon-on-insulator materials and devices, and copper wiring for integrated circuits. Current research focuses on new materials and device structures for ever-smaller transistors, with channel lengths of some experimental devices now less than 10 nm. At the same time, the potential of carbon nanotube transistors and other novel molecular-scale devices is being explored for applications in information processing and storage.



Data from The Age of Spiritual Machines, Ray Kurzweil (1999)

Figure 2. A combination of continuous miniaturization and innovation has resulted in an ever-decreasing cost of computation, shown here as additions-per-second available at a cost of $1,000 between 1940 and 2020.

Disk drives have increased in recording density by 8 orders of magnitude since the first RAMAC shipment almost 50 years ago, an increase sparked in part by innovations from what was originally called the IBM San Jose Research Lab and is now known as the Almaden Research Center. These advances include the introduction of the magnetoresistive (MR) read head in 1991 and the giant magnetoresistive (GMR) read head in 1997. The GMR effect results from a phenomenon first described by Stuart Parkin of IBM Almaden— oscillatory exchange coupling of electron spins through a thin tunneling barrier.

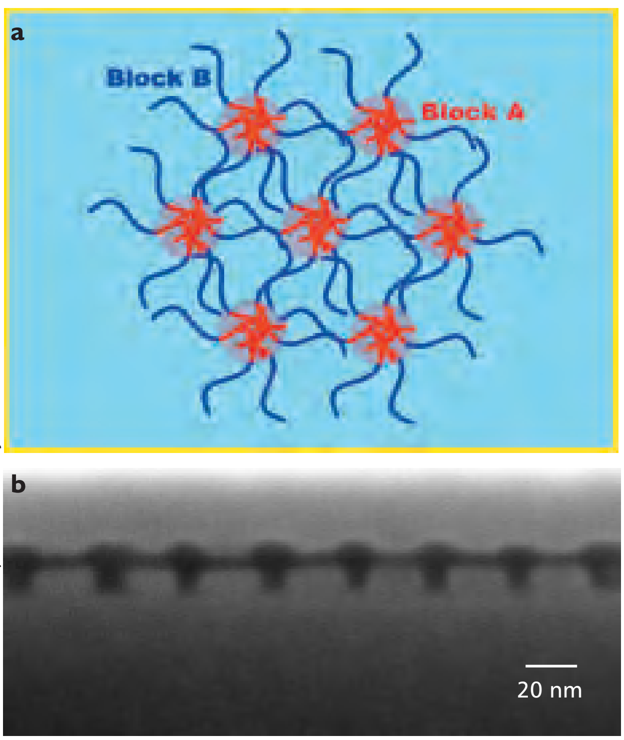
Recording heads and magnetic-disk coatings that take advantage of this oscillatory exchange coupling are used in most disk drives sold today. Current research in micromagnetic systems focuses on spintronic devices such as the magnetic RAM, which is based on magnetic tunnel junctions. Three-terminal or transistor-like spintronic devices are also of intense interest.

Harnessing light

The potential uses of light in communications and information storage motivated research in nonlinear optics. Peter Sorokin invented one of the first lasers, the four-level or dye laser, in 1966. Marshall Nathan and co-workers demonstrated the diode laser simultaneously with a team at General Electric Co. Jerry Woodall, Hans Rupprecht, and others made advances in solid-state lasers based on heterojunctions, the boundaries between two different semiconductor materials. Less well known is that in the late 1980s, a small team at IBM's Zurich Research Laboratory in Switzerland developed high-reliability semiconductor lasers for amplifying signals in optical fibers. By the early 1990s, that same team was manufacturing most of the world's supply of fiber-amplifier lasers to meet the burgeoning need generated by the rapid expansion of the Internet. The path from invention to innovation can be circuitous.

Many times over the years, this focus on application and innovation has stimulated the discovery of entirely new physics. For example, experiments with field-effect transistors resulted in IBM's early entry into complementary metal-oxide-semiconductor transistor manufacturing, and set the stage for the 1966 observation of the quantum confinement of conduction electrons at the silicon/silicon dioxide interface in transistor structures. The observation of the two-dimensional electron gas by Alan Fowler, Frank Fang, Web Howard, and Philip Stiles proved a seminal event in the development of condensed-matter physics and demonstrated the essential validity of effective-mass theory at remarkably small dimensions. Leo Esaki, Ray Tsu, and Leroy Chang began to envision and investigate designed quantum structures—which are based on interfaces between lattice-matched compound semiconductors—early in the 1970s. Ever since, the study of electronic systems of minute dimensions has ranked among the most exciting areas of condensed-matter physics.

Another example of truly groundbreaking research motivated by a healthy interest in applications is the work of Gerd Binnig and Heini Rohrer. In the early 1980s, the two scientists were searching for a better way to characterize the thin tunnel junctions used in IBM's Josephson-junction computer project. In 1986, they received the Nobel Prize for their invention of the scanning tunneling microscope (STM). The consequences of the invention of the STM—the ensuing revolution in surface science, metrology, and microscopy; the subsequent inven-



Charles Black and Kathryn Guarini, IBM T. J. Watson Research Center

Figure 3. Phase separation in a thin film of block copolymers results in columnar arrays with hexagonal symmetry, shown schematically (a). The pattern is transferred to an exploratory silicon memory device shown in a cross-sectional image (b).

tions in scanning probe lithography; and new physics revealed by single-atom manipulation—continue to unfold (Figure 1).

Finally, some of the many outstanding contributions to theoretical and computational science made by IBM scientists have been motivated by the concerns of information technology. Studies of the electronic structure of surfaces and itinerant magnetism provided the theoretical underpinnings for semiconductor and magnetic-recording technologies. Rolf Landauer and Charles Bennett, perhaps more than any other individuals, helped to bring information into physics as a fundamental construct on the same level as entropy. This line of research continues today, with exciting developments in the theory of quantum information connected to fledgling experiments in quantum information processing. Ready access to fast computers has spawned advances in computational science, from the beginnings of quantum chemistry to current research in computational biology.

Future research

As the devices of information technology approach atomic and molecular dimensions, progress in miniaturization must some day come to a standstill. However, with the leading microelectronics manufacturers now fabricating silicon chips with lithographic features as small as 90 nm, there remains much new physics to be discovered. And many things must be invented before the complex systems of information technology are routinely designed and manufactured with essential structures specified at the atomic scale. With this in mind, we will continue to explore new devices with the potential to more efficiently process, store, and communicate information.

To combat the ever-increasing costs of ever-finer lithographic resolution, we are increasingly exploring processes of natural patterning, or directed self-assembly, to build technologically useful structures (Figure 3). Finally, as information technology pervades society, an increasing fraction of our research touches on applications of information technology rather than on the underlying hardware. For instance, we currently see a rapid growth in the sales of information technology to customers in the life-sciences industry. We have found that there is great value in understanding the scientific problems faced by these customers, and great potential for exciting science at the interface between mathematics, biology, and physics—with physicists bringing unique tools and points of view to the enterprise.

We are sure that physicists will continue to play key roles in charting our course to create the future of information technology, wherever that might lead.

Further reading

Bashe, C. J.; Johnson, L. R.; Palmer, J. H.; Pugh, E. W. *IBM's Early Computers*; MIT Press: Cambridge, MA, 1985; 738 pp.

Pugh, E. W. *Building IBM: Shaping an Industry and Its Technology*; MIT Press: Cambridge, MA, 1995; 432 pp.

The 25th anniversary issue of the *IBM Journal of Research and Development* (*IBM J. Res. Develop*. **1981**, *25* (5), 353–846) highlights some of the technical and scientific accomplishments achieved during the first quarter century of this journal. It is available at http://domino.research.ibm.com/tchjr/journalindex.nsf/ResVolumes?OpenView&Start=1&Count=1000&Expand=24.4#24.4.

The Millennium issue (*IBM J. Res. Develop*. **2000**, *44* (3), 310–443), available at http://domino.research.ibm.com/tchjr/journalindex.nsf/ResVolumes?OpenView&Start=1&Count=1000&Expand=5.2#5.2, goes into greater detail about more-recent IBM highlights and research programs.

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BIOGRAPHY

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