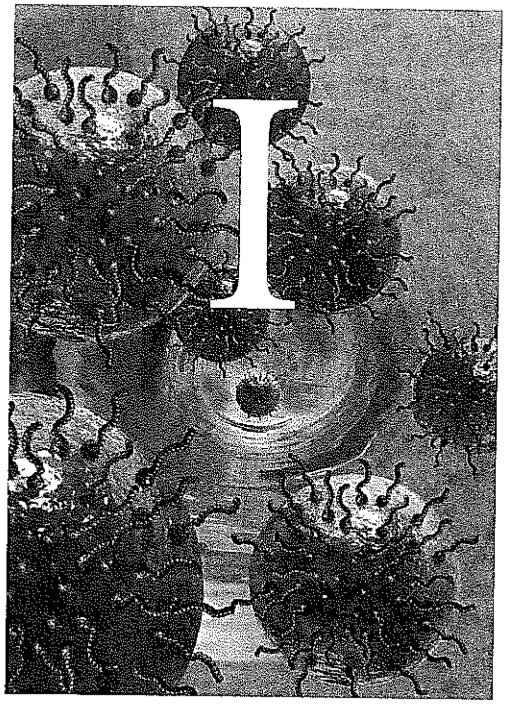



## IBM

Once IBM committed to the computerization of its product lines, it put itself on a path toward playing a large role in nanotechnology. Innovation in computing is closely tied to miniaturization, so at some point that innovation would have to take place at the nanoscale. Big Blue, with its outsize role in the history of computing (the computer industry was once characterized as "IBM and the Seven Dwarves"), and its enormous research capacity, began looking ahead to the nanoelectronics era by (at the latest) the early 1970s. Yet, IBM did not merely ride Moore's Law into the nanoscale—it was often far out ahead of Moore's Law, calling for the adoption of seemingly far-fetched techniques that today are the mainstays of nanotechnology research.

### Corporate Research in the Golden Age

The trend toward miniaturizing electronic components has been in place since before World War II, with miniature vacuum tubes for proximity fuses and field radios. With the invention of the transistor at Bell Laboratories in 1947, though, miniaturization took on a new urgency. Reducing the size of solid-state components would make them faster and potentially cheaper. The tendency of the smallest commercial components to get smaller at a steady exponential rate is known as Moore's Law, after an observation by Gordon Moore of Fairchild Semiconductor (later Intel) in 1965.

Even before 1965, though, electronics firms noticed this trend and wondered how to keep up with it. Silicon Valley firms such as Intel and Fairchild decided—as the nickname for their region indicates—to do so by sticking with silicon transistors, manufactured with optical lithography. They did so partly because the most successful Silicon Valley firms had very small research units, and focused almost exclusively on a very small set of capabilities. Thus, they were forced to act in concert with large networks of suppliers, and therefore needed to innovate in small, steady, incremental steps, avoiding large, disruptive changes in manufacturing as much as possible.

This innovation model was mirrored, to some extent, by Asian electronics firms, but differed considerably from that of firms in Europe and the northeastern United States. There, companies like RCA, Westinghouse, AT&T, IBM, and Philips had large, autonomous research units. These companies often had oddly diverse arrays of corporate divisions (RCA, for instance, owned the Hertz rental car company); corporate research was one division among many, expected to pay for itself but not overly burdened with communicating to the other divisions.

This was particularly possible in Cold War America because the federal government funded so much basic research. Companies like IBM could secure federal grants, but they also benefited from tax incentives that rewarded corporate spending on basic research. Thus, research on topics very distant from IBM's immediate technological needs could serve as a separate profit center within the company.

This resulted in a golden age for corporate research, when companies like IBM and AT&T hired the world's leading architects to build lavish research "campuses" in pastoral retreats so that they could lure the world's leading scientists to work on topics of their own choosing. In fields such as surface science and information theory, IBM Research and Bell Laboratories could amass enough research talent to eclipse any university or government laboratory.

IBM built not just one, but a whole network of such research centers, three of which have become famous in the history of nanotechnology. The Thomas J. Watson Research Center in Yorktown Heights, New York, was the lab closest to corporate headquarters, and therefore the one that usually most resembled corporate culture in the rest of IBM. The IBM Zurich lab, conversely, was farthest from headquarters both physically and culturally, and often embarked on strange tangents—for which its researchers garnered four Nobel Prizes. IBM Almaden, located near San Jose, operated most like a Silicon Valley outfit, generally orienting its research to a much shorter time horizon.

## Vertically Integrated Quasi-Monopoly

IBM and its large, established East Coast peers operated as de jure or de facto monopolies in their industries. Their ability to enforce intellectual property rights, for instance, was largely curtailed by consent decrees with the U.S. Department of Justice's antitrust division. IBM and its peers were also highly vertically integrated, manufacturing almost all aspects of their products and processes rather than outsourcing to other firms. Taken together, these three characteristics—quasi-monopolistic situation, vertical integration, and a requirement to share intellectual property—would have an important, if indirect, influence on the course of nanotechnology.

For one thing, it led IBM and its peers to a number of inventions that Silicon Valley firms were then in a better situation to commercialize. For instance, the metal-oxide-silicon (MOS) transistor that is the mainstay of today's computer chips was invented at RCA and developed at IBM, but was only turned into a commercial success by Silicon Valley firms. Because MOS technology only achieves high efficiencies at very small length scales and large degrees of integration, adoption of MOS encouraged Silicon Valley firms to pursue very large-scale integration of their chips, with chip features trending quickly toward the nanoscale.

IBM and its peers, as vertically integrated monopolies, also tended to have technological requirements that were completely different from any other firm's. IBM was therefore known for its tendency to attempt highly idiosyncratic technological approaches. These could be justified because even if they failed to solve the company's technological problems, such approaches would still contribute to the firm's basic research effort. This can be clearly seen in IBM Zurich's two sets of Nobel Prizes, both of which grew out of a large but abortive attempt to build a supercomputer from superconducting, rather than semiconducting, logic elements. One prize went to Georg Bednorz and Alex Müller for their successful search for an esoteric and unintuitive class of superconductors—a search conducted largely after the supercomputer effort had ended.

The other prize went to Heinrich Rohrer and Gerd Binnig for their invention of the scanning tunneling microscope (STM). Binnig and Rohrer originally set out to find a way around manufacturing problems that the supercomputer project was experiencing. At almost any other company, however, the approach to such problems would have been to buy or borrow an existing instrument such as an electron microscope. IBM Research was so large, and so oriented to basic problems, though, that Binnig and Rohrer felt justified in spending several years to develop an entirely new class of instrument, such that they only succeeded after it was clear that the supercomputer project would be ended. Nevertheless, they were able to win managerial support for continuing STM development by demonstrating its relevance in basic research areas that IBM was well represented in, especially surface science.

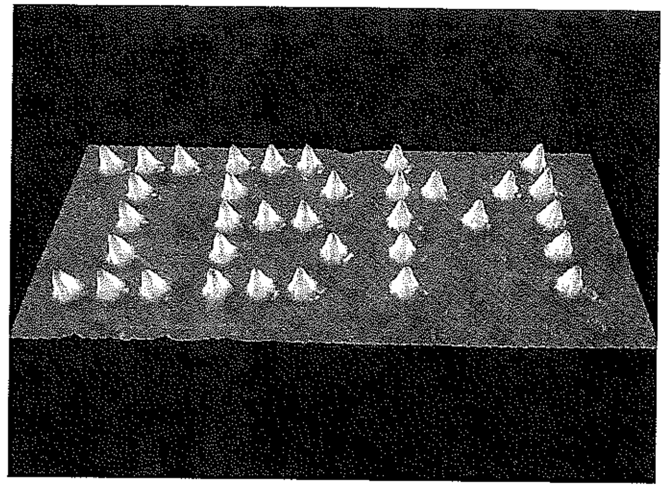
## Alternatives to Silicon

Because it was a vertically integrated quasi-monopoly with a large research unit (at least until the 1990s), IBM's approach to the miniaturization of electronics differed considerably from Silicon Valley firms. IBM only needed to coordinate changes in manufacturing process internally, so it could (in theory) change more elements of manufacturing more radically than the interdependent network of Silicon Valley firms. IBM could draw on its basic research advantage to identify what those radical changes should be, whereas Silicon Valley firms focused their own research on incremental changes in manufacturing. And, as a quasi-monopoly, IBM executives believed they could plow money and time into preparing for radical changes without having to worry about being overtaken by competitors in the meantime. By the early 1990s, those executives were being proven wrong, but until then their strategy had several repercussions for nanotechnology.

One was that IBM ardently advocated for approaches to microelectronics manufacturing that differed substantially from industry norms. For instance, where Silicon Valley firms have stuck with optical lithography as the main technique for creating tiny features in chips, economists estimate the IBM put as much as $1 billion into developing X-ray lithography as an alternative. IBM also put substantial money into—and trained a generation of scientists in—other alternative techniques, such as electron beam lithography and ion beam lithography. Many of those researchers eventually left IBM for academic positions, several (such as Evelyn Hu) as heads of Nanoscale Science and Engineering Centers or facilities in the National Nanotechnology Infrastructure Network. IBM researchers were also instrumental in creating institutions that today support the nanotechnology community. IBM microelectronics guru Robert Keyes, for instance, was the driving force behind the Gordon Research Conference on Nano- (originally Micro-) structure Fabrication.

IBM encouraged its researchers to move even farther from the microelectronics mainstream in search of a new platform. The superconducting supercomputer project mentioned above, for instance, cost at least $100 million over 15 years. Had it succeeded, it could have displaced silicon as the dominant material of microelectronics, and staved off the Silicon Valley challenge to IBM. As it was, a surprisingly large number of today's nanoscientists got their start either in the IBM superconducting supercomputer project, or in parallel defensive projects at IBM's East Coast peers (especially Bell Labs).

Even further afield, IBM launched the first detailed investigation of molecular electronics (the idea that single—or small numbers of—organic molecules could replace transistor logic elements) in the early 1970s, and (in conjunction with Stanford) the first demonstrations, in the 1980s, that probe microscopes could be used to read and write bits of information at the nanoscale. Neither of these programs resulted in commercial products in the short term—as they would likely be expected to at a Silicon Valley firm—but over a multi-decade timescale they have moved closer to IBM's product line.



*IBM Fellow Don Eigler used a custom-built microscope to spell out the letters IBM with 35 xenon atoms.*

## Recognition and Retrenchment

The early 1990s held mixed prospects for IBM's role in nanotechnology. On the one hand, Big Blue continued to make stunning basic research contributions that attracted positive attention both to the company and to the nanotech enterprise more generally. For instance, in 1993 Donald Bethune's group at IBM Almaden co-discovered single-walled carbon nanotubes, thereby opening up an entirely new field of nanotech research. Even more spectacularly, in 1989 Don Eigler's group, also at Almaden, used its low-temperature STM to move individual xenon atoms into place to spell out the letters "I-B-M"—one of the most widespread images in all of nanotechnology. Eigler's group has gone on to demonstrate existence proofs for many of the world's smallest devices: atomic corrals, quantum mirages, and molecular adders.

The early 1990s also saw the collapse of IBM's mainframe market, however, as well as a painful forced transition from bipolar junction logic to MOS. Big Blue neared bankruptcy, and emerged from restructuring as a much leaner company with no claim to monopoly status and much less vertical integration. IBM Research slimmed considerably, and reoriented to the much nearer term. Perhaps the most successful outcome of this reorientation was the Almaden lab's rapid commercialization of the giant magnetoresistance (GMR) effect for magnetic-storage media. The GMR effect was discovered by academic researchers, but in a field where IBM scientists had deep roots, such that it could take advantage of it in very short order. Because GMR depends on the deposition of very thin films, it can be considered a subfield of nanotechnology. Indeed, the Nobel Prize committee hailed it as such in awarding the 2007 Physics laureate to GMR's co-discoverers.

As the GMR example shows, the 1990s saw a convergence of the IBM and Silicon Valley approaches to innovation. On the one hand, as IBM lost its quasi-monopoly, it was forced to draw its researchers' attention to the immediate needs of its product line. On the other hand, as Moore's Law became more difficult to sustain, Silicon Valley firms began to see a greater need for basic research. Thus, as IBM recovered it became more integrated into Silicon Valley, often as the research arm of large coalitions of firms. Because of its long history in the field, and its unique position in the microelectronics industry, IBM was well-placed to influence national nanotechnology policy in several countries. In Switzerland, for instance, Heinrich Rohrer was instrumental in organizing the national government's nanotechnology initiative, and many of the beneficiaries of that initiative have been researchers who have either been IBM employees or have deep collaborations with IBM.

In the United States, IBM has a strong reputation as a political player, with members of the Watson family tied closely to both Democratic and Republican circles. Many leading figures in the American science policy establishment have either come from or gone to IBM: Ralph Gomory (president emeritus of the Sloan Foundation), Lewis Branscomb (former director of the National Bureau of Standards), and Erich Bloch (former director of the National Science Foundation). In nanotechnology, IBM's Director of Physical Sciences, Thomas Theis, has been an influential proponent of the National Nanotechnology Initiative through testimony to Congress and membership on the National Research Council committee for review of the NNI that produced *Small Wonders, Endless Frontiers*.

Scientometric studies of the nanotechnology enterprise in, for example, the *Journal of Nanparticle Research*, consistently show that IBM is first or second among patent assignee institutions in nanotechnology, near the top in most-cited nanotechnology patents, and in the top five in most-cited journal articles in nanotechnology. In its collective contribution to nanotechnology, IBM eclipses all other corporate rivals—especially since its closest competitor, Bell Labs, no longer exists. Although other firms, such as Intel, have clearly made significant contributions in nanotechnology, IBM is probably unparalleled in its ability to coordinate its research efforts across the entire spectrum from near term to far term. In almost any area of nanotechnology research, particularly (but not limited to) nanoelectronics, current or former IBM employees are likely to be leading contributors.

**See Also:** Carbon Nanotubes; Microscopy, Scanning Tunneling; Moore's Law; Nanoelectronics.

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# Images

The nanoscale is invisible to unmediated sensory perception, and yet images of it continue to emerge. Nanoscale images produced by scientists generally stem from scanning probe microscopes. What these microscopes do, however, is more akin to "touching" than "seeing," and the data generated must be converted by computer software into a visual representation. This creates debate about