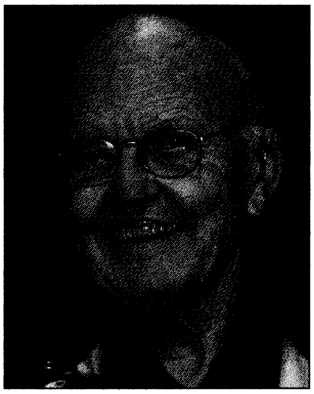
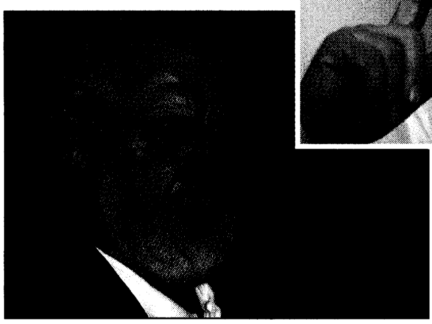
Silicon technology has come a long way. In late 1947, scientists at Bell Laboratories invented the transistor, ushering in the computer age. John Bardeen, Walter Brattain, and William Shockley won the 1956 Nobel Prize for the invention, but their transistor was not ideal. Although it was much smaller and more reliable than the vacuum tubes it replaced, manufacturers still had to solder thousands of transistors and other components to a circuit board to construct even the most rudimentary computers. "By that time people could visualize electronic equipment that couldn't be built—it was too expensive, too bulky, and too unreliable," Kilby recalls.



**Integrator.** Jack Kilby produced the first integrated circuit.

In 1958, Kilby was stuck in the laboratory; just hired by Texas Instruments, he hadn't earned the vacation time to get away for the summer. But Kilby made good use of the extra time in the lab: He came up with a radical solution to the assembly problem.

Instead of taking lots of individual transistors and soldering them together, Kilby put all the components of a circuit on a single wafer of semiconducting crystal such as germanium or silicon. He did this by taking a wafer of germanium, covering bits of it with black wax, and then exposing the wafer to acid, so that areas that weren't protected by the wax were etched away. In this way, he carved transistors, resistors, condensers, and other elements on the same wafer and out of the same materials—all layered and wired on one crystal. This "integrated circuit" avoided the labor problems, space constraints, and quality-control issues that plagued circuit boards assembled from individual transistors. Kilby and a competitor, the late Robert Noyce of Intel, are credited with inventing the integrated circuit that put the computer revolution in high gear.



**Souped-up silicon.** Herbert Kroemer and Zhores Alferov (*inset*) saw the way to high-speed solid state components.

CREDITS: (TOP TO BOTTOM) T. SHARP/AP; D. LOVETSKY/AP; P. KLEIN/AP

Kroemer wins his Nobel Prize for refining the basic transistor that made it faster and more efficient. The key to this invention lies in modifying the flow of negatively charged electrons and positively charged "holes"—spaces vacated by electrons—through semiconductors. Though electrons carry the charge, the holes act as if they were particles that carry a positive charge.

In an ordinary transistor, when electrons flow in one direction, holes swim upstream in the opposite direction. Unfortunately, the bigger the reverse flow of holes, the less amplification the transistor gives—the less powerful it is. The so-called heterojunction bipolar transistor solves this problem by using layers of two complementary semiconductors (such as gallium arsenide with aluminum gallium arsenide), whereas traditional transistors used just one (such as silicon). Electrons can cross from one semiconductor layer to the other easily, but holes cannot (or vice versa, depending on the configuration). By doing this, "you prevent holes from flowing in the reverse directions—they run into a potential barrier," explains Jim Merz, a physicist and vice president at Notre Dame University in Indiana. "This was Kroemer's idea; he realized that it had huge implications."

Better yet, Kroemer realized—as did Alferov—that these heterogeneous semiconductors could be turned into lasers. By arranging materials in the proper fashion, it's possible to create a trap for electrons and holes—a region where they can flow in but can't flow out. When an electron and a hole meet inside this trap, they recombine, releasing light. This light, in turn, incites more trapped electrons and holes to recombine. It's just like a traditional laser, but it can be made out of semiconductors.

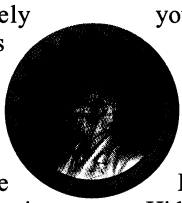
Kroemer and Alferov's brainstorm led to the development of radio satellites, base stations for mobile phones, fiber optic cables, and CD players, notes semiconductor laser researcher Al Cho of Lucent Technologies' Bell Laboratories in Murray Hill, New Jersey. "I think they certainly are pioneers."

—CHARLES SEIFE

CHEMISTRY NOBEL

## Getting a Charge Out of Plastics

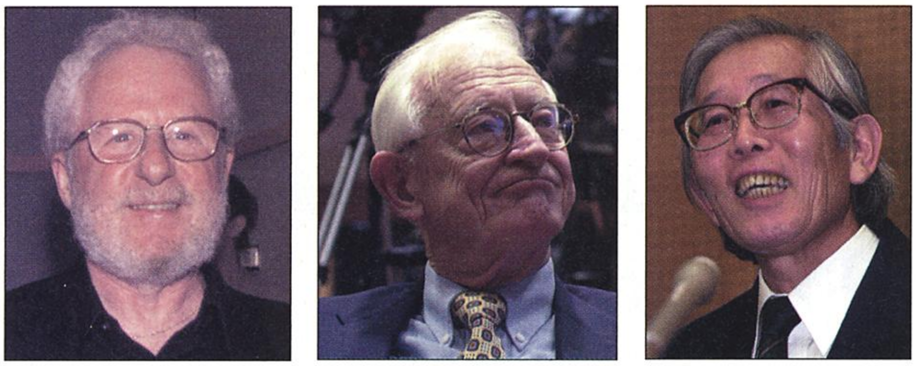
Polymers generally make good insulators: Witness the plastics shrouding the wires in your home. But this year's Nobel Prize in chemistry was awarded to a trio of researchers—Alan Heeger of the University of California, Santa Barbara; Alan MacDiarmid of the University of Pennsylvania in Philadelphia; and Hideki Shirakawa of the University of Tsukuba in Japan—for discovering that plastics can be made electrically conductive. The discovery paved the way for revolutionary applications such as full-color displays for cellular phones and plastic electronics for computerized merchandise, as well as still-futuristic hopes of computing with molecules and creating cheap, large-area solar cells.



The initial discovery of electrically conductive plastics stemmed from a wonderful bit of serendipity. In an experiment in the early 1970s, one of Shirakawa's students accidentally added excess catalyst to a brewing batch of plastic called polyacetylene. The result was a shiny silvery film. Shirakawa told MacDiarmid of his discovery during a visit to Kyoto University in 1975. "When MacDiarmid saw it, he was very surprised," says Shirakawa.

It turned out MacDiarmid and Heeger —who was also at the University of Pennsylvania at the time—had been experimenting with metallic-looking films from polymers made from inorganic building blocks. They were trying to learn more about the changes that take place as materials change from insulators to metals. The inorganic polymers were scientifically interesting because they showed hints of this change, but they couldn't be modified easily like organic polymers, says Heeger. So when MacDiarmid returned to Pennsylvania and told Heeger of Shirakawa's work, "I said, 'This is what we're looking for,' " recalls Heeger.

MacDiarmid invited Shirakawa to visit the University of Pennsylvania, and the researchers quickly set about modifying the polymers and testing the results. In one case, they used an iodine vapor to oxidize the film, a treatment they knew could change the film's optical properties. But that was the least of the changes: The conductivity shot up by 10 million times. Polyacetylene, like other conducting polymers discovered since, is a chainlike molecule with alternating double and single bonds. When excess charges are added to the molecule—as happens during oxidation—these charges can then hop along the alternating bonds with



**Plastic electronics.** Alan Heeger, Alan MacDiarmid, and Hideki Shirakawa (*left to right*).

relative ease. That discovery created a field that has been hopping ever since.

Despite widespread agreement among chemists that the trio selected by the Nobel committee are worthy recipients, the selection is "rather controversial," says Stephen Forrest, a materials scientist at Princeton University. Many applications of plastic electronics, it turns out, are based on more recently discovered relatives of the metallic polymers that Heeger, MacDiarmid, and Shirakawa originally experimented with. These behave like silicon and other semiconductors. The Nobel committee chose not to honor the discoverers of these materials. Forrest and most others call that understandable. "Now the research has more emphasis on semiconducting polymers," says Zhenan Bao, a chemist at Lucent Technologies' Bell Laboratories in Murray Hill, New Jersey. "But it's all based on [Heeger, MacDiarmid, and Shirakawa's] early concepts."

Such concerns haven't clouded the moment for the Nobel recipients. "It's been a wonderful week," says Heeger, who adds that the prize came as a "complete surprise." MacDiarmid says that when he was told the news by a friend who saw it on the World Wide Web, he didn't believe it. "I thought it must be a hoax. But then I immediately got calls from reporters in France and Germany and thought maybe this is real."

The reaction has been particularly enthusiastic in Japan, where Shirakawa's selection is the first chemistry Nobel Prize awarded to a Japanese researcher in 19 years. It was front-page news the following morning, and throughout the week newspapers ran large photos, such as shots of Shirakawa receiving bouquets of flowers from students at Tsukuba University. And it prompted the editors at the *Mainichi Shimbun*, one of Japan's largest daily newspapers, to say they hoped the award would serve as a catalyst to "update the nation's dilapidated and cramped research facilities."

–ROBERT F. SERVICE

With reporting by Dennis Normile in Tokyo.

CREDITS: (CLOCKWISE FROM TOP LEFT) P. KLEIN/AP; D. LOH/AP; K. SASAHARA/AP; P. SAKUMA/AP; D. ENGLE/AP

ECONOMICS NOBEL

## Dealing With Biases And Discrete Choices


To a biologist, "micro" means bacterium-sized. To an economist, it means people-sized. And this year's Bank of Sweden Prize in Economic Sciences, given in honor of Alfred Nobel, goes to two researchers who gave the field of microeconomics—the study of individuals' economic behavior—new tools to help draw conclusions from imperfect data.

As any scientist knows, statistical investigations are prone to error; inadvertent biases in choosing the sample or systematic errors can doom a project. The situation is even dicier for economists who take statistical samples of complex, semirational objects like human beings.

James Heckman of the University of Chicago wins half of this year's prize for coming up with ways to deal with selection biases. He developed two methods that formalize the handling of such biases, and then he used them to analyze things such as how wages affect the behavior of married women in the labor market.

Burton Singer, a demographer at Princeton University, says he believes Heckman's best achievements were not in the mathematical methods, but in what he was able to do with them. For instance, Heckman analyzed whether African Americans in Southern states like South Carolina were being helped more by education improvements or by the civil rights movement. "Government legislation had a more profound impact than schools per se," as did activism in the African-American community, says Singer, who notes that this surprising conclusion "had almost been ignored by the economic community."

**Individual choices.** James Heckman and Daniel McFadden (*inset*).

Heckman also thinks his most valuable work is applied rather than theoretical. "Economics is a field where you're solving real problems," said Heckman by telephone from Brazil, where he and his students are studying education and economics. "Being able to tackle real problems has always been an attraction for me."

Daniel McFadden of the University of California, Berkeley, tackled a different conundrum: how to quantify discrete choices rather than continuous ones. "Before McFadden did his work, economists were concerned with buying amounts—how many oranges a consumer buys, et cetera," says Charles Manski, an economist at Northwestern University in Evanston, Illinois. "But many important choices are discrete: Do you go to college or not? Do you buy an auto or not?"

McFadden had two insights that allowed him to tackle discrete problems. First, he came up with a way of comparing apples and oranges—or buses and cars, as the case may be. "For instance, if you choose to commute to work, you can go by bus, by rapid transit, or by auto," says Manski. "If you think of an auto as a bundle of characteristics—values for travel time, cost, and comfort—and a bus as a different bundle, you can compare them." Now that all these different choices were directly comparable, he could model how consumers behave when given those choices.

This is where McFadden's second insight comes in: He turned the discrete choices into more continuous, tractable functions by looking at them in terms of probabilities. For instance, a consumer might have, say, a 20% chance of taking a car to work, a 40% chance of taking a bus, and a 40% chance of taking rapid transit. This method, inspired by similar approaches used by psychologists, turned discrete problems into continuous ones—and it led to his helping design the Bay Area Rapid Transit system.

Marketers, sociologists, political scientists, and others are indebted to McFadden's methods, says Steve Lerman of the Massachusetts Institute of Technology: "The number of applications, in both marketing and economic analysis, must be in the thousands—maybe even higher."

–CHARLES SEIFE