Chem 202 The Case of Henrik Schon

1) Read the article from Science magazine entitled "Winning Streak Brought Awe, then Doubt". (for discussion Tuesday, Feb. 25)
   a) Explain how the FET device shown on p. 35 works and what it does.
   b) How does a sputtering machine work? Why was Schon's work with sputtering of aluminum oxide so important in getting organic FETs to work properly? What was the reaction of the scientific community to his paper on the device?
   c) Schon next turned to superconductors. What was he able to demonstrate? Why was he seriously considered as a candidate for a Nobel prize?
   d) What made other scientists begin to suspect Schon's results?
   e) Why did Science report that Schon's work was "under a cloud" in July 2002?

2) Read the article from Science magazine entitled, "Pioneering Physics Papers Under Suspicion for Data Manipulation" (for discussion Tuesday, Feb. 25)
   a) How and when did the duplicate figures in papers by Schon come to light?
   b) Why was Paul McEuen so concerned with the background noise in some of Schon's figures?
   c) What was the response of the scientific community and of Schon's co-workers?
   d) Did the people who reviewed Schon's papers screw up, or did they do their jobs properly?

3) Read "Unrealistic precision: Characterization of Sputtering Process," a section taken from the Beasley committee's final report on Schon's alleged misconduct. (for discussion March 4)
   a) Why did Schon write the "Sputtering" paper? Where was it published?
   b) What does Figure 53 show and why was the Beasley committee dubious that it represents real data?
   c) Figure 54 shows another figure taken from the "Sputtering" paper. What are the problems that the Beasley committee found with this figure?
   d) How did Schon respond to the committee? What was their main conclusion?

4) Read the last article from Science (for discussion March 4).
   a) What happened to Schon? To his collaborators? Was justice done?

5) What similarities and differences are there between the Schon case and the rise and fall of bond-stretch isomerism?
Even in the best of times, 95% of Jan Hendrik Schön’s experiments fizzled out. It’s the other 5% that made him one of nanotechnology’s brightest stars and the envy of physicists worldwide. In paper after paper, he and his collaborators reported that a simple turn of a dial could transform normally poor electrical conductors into semiconductors, metals, or even superconductors, a malleability never seen before. That opened up entirely new vistas for exploring the physics of materials—the stuff of Nobel Prizes. 

Today, though, few researchers would trade places with Schön, a physicist at Bell Laboratories, the research arm of Lucent Technologies in Murray Hill, New Jersey. On 10 May, Bell Labs officials launched an investigation of Schön’s work, after outside researchers revealed what appears to be duplication of data in multiple papers (Science, 24 May, p. 1376). Schön is the lead author on all the papers under scrutiny and the only author whose name appears on all. The investigation is the first of its kind in the 77-year history of Bell Labs, the world’s most famous corporate research outfit.

Schön says he stands behind his measurements and is doing everything he can to cooperate with the inquiry, which is being conducted by an outside committee and is expected to be completed by the end of the summer. But, until then, a cloud hangs over a spectacular body of work.

Some researchers say that the suspect data have cast doubt on all of Schön’s results. “I can’t trust any of the work,” says Harvard University chemist and nanotechnology expert Charles Lieber. Others, however, point out that much of the disputed data seems to be supporting material, not the primary results in each paper, which detailed the observations of everything from high-temperature superconductivity to quantum-mechanical signatures never before seen in organic materials.

Unfortunately, Schön’s most provocative results have not been independently verified, despite years of effort by other labs and tens of millions of dollars spent on research in the area. Even before the storm of controversy broke, other scientists were starting to raise questions about how Schön and his colleagues achieved their stunning results and why no one else has been able to repeat them.

In interviews conducted over the past 6 months—most of them before the investigation began—the Bell Labs team and others in the field retraced the whirlwind trajectory of the work and weighed its enormous promise against those simmering questions. The answers, when they come, will have enormous significance not just for the fate of one bright young researcher but also for scientists around the world trying to follow his lead, and for the future of one of the hottest ventures in condensed-matter physics.

**A question of speed**

That venture got its start in Bell Labs’ room 1E318, a somewhat dingy, crowded lab located one floor below the birthplace of the transistor. The room was the longtime lab of superconductivity physicist Bertram Batlogg. One day in the mid-1990s, Batlogg and his colleagues were brainstorming ideas about work on plastic electronics when he hit on one that he just had to try.

A Bell Labs team led by physicist Ananth Dodabalapur, now at the University of Texas, Austin, had succeeded in making field effect transistors (FETs) using a variety of organic materials laid down in thin films. FETs are the bedrock electrical switches of computer circuitry. In a typical version, a pulse of electrons sent to one electrode, called the “gate,” creates an electric field that repels electrons sitting in the semiconductor lying directly below, effectively spiking it with positive charges. These charges boost the conductivity of this semiconductor “channel,” making it easier for electrons to flow through this channel between two other electrodes. And, presto, the device switches from off to on (see diagram on p. 35).

But electrons don’t move at the same rate through all semiconductors. Dodabalapur’s organic transistors weren’t about to give Intel’s inorganic ones a run for their money. They were painfully slow. Electrical currents crept through the organic channels at a pace orders of magnitude below their speed through even the worst silicon-based devices. The team didn’t know whether organics were inherently slow conductors or whether the problem lay in the way the devices were constructed.

Batlogg suggested a way to find out. In the thin organic films that Dodabalapur’s team was using, the organics invariably organized spontaneously into tiny crystallites, like gravel on a path. It was possible that charges were zipping through the perfectly ordered organics within each crystallite but were getting hung up at the ragged borders as they hopped from one crystallite to the next. Batlogg suggested growing larger single crystals and using them to measure the speed of electrons. Because single crystals don’t have grain boundaries, the researchers would see what the materials could really do.

The catch was that making high-quality single crystals out of organics is much more easily said than done. “Organics are synonymous with crappy stuff,” Batlogg said in February. Even the best organic...
crystals typically harbor 1% to 2% impurities, often solvent molecules left over from their original synthesis. Their presence can disrupt the regular crystalline order of the material enough to make it impossible to grow a single crystal.

Dodabalapur’s team members were too busy with their thin-film transistors to steer their research in a new direction. So, Batlogg offered to help. In 1997, he and Bell Labs chemist Bob Laudise recruited Christian Kloc, a chemist then based in Konstanz, Germany, who was an expert at growing crystals. Kloc quickly hit upon a new strategy for both purifying organics and growing crystals at the same time. Kloc’s progress meant Batlogg needed another set of hands to put the crystals through their electrical paces. His longtime friend (and Kloc’s former boss) Ernst Bucher in Konstanz recommended Schön, who jumped at the opportunity and left for New Jersey even before finishing his Ph.D.

Schön set up shop at Batlogg’s lab, and the results came quickly. When Schön slapped electrodes on a variety of different organic crystals, none came even close to matching the speed of the standard crystalline silicon semiconductor. The best organic, called pentacene, just kept pace with low-grade amorphous silicon, a semiconductor commonly used in solar cells. Dodabalapur’s team had already achieved similar speeds with their thin-film FETs—devices that were chock-full of grain boundaries. This was bad news for organic-crystal research. If grain boundaries didn’t hinder the flow of current, then there wasn’t much anyone could do to improve the crystals’ plodding speed. Plastic electronic devices, it seemed, were destined to be slow.

Up for a challenge

The science of working with single crystals of organics, however, was just picking up speed. Horst Stormer—a Nobel Prize–winning physicist who was then at Bell Labs but has since moved to Columbia University in New York City—spurred the team on by issuing a challenge. “He said [that] if any semiconductor is decent, you can make it into a transistor,” Batlogg recalled. Transistors had already been made with thin films of organics. But those are relatively simple devices to make. Researchers place metal electrodes on a wafer of inorganic crystalline silicon, then add a layer of the soft organic material atop the wafer’s tough ceramiclike surface.

What Stormer was proposing was much harder: starting with one of Kloc’s fragile, millimeter-sized single crystals of organics as the substrate and planting metal electrodes on top. The upside-down approach was necessary because organics grown on wafers spontaneously form tiny grains, or crystallites. As a result, single-crystal FETs must be built from the crystal on up. “The difficulty was the prospect of putting down hard materials on soft materials, held together only with weak van der Waals bonds,” said Art Ramirez, a physicist at Los Alamos National Laboratory in New Mexico, during an interview in March. “You have to do the deposition very, very carefully.”

To succeed in making a single-crystal or-ganic transistor, Schön needed another key ingredient: a thin insulating barrier to prevent charges from shuttling back and forth between the electrodes when they’re not supposed to do so. All transistors rely on such insulating barriers, which come in a wide variety of chemical flavors.

Schön decided to make his insulator out of aluminum oxide, a decision that became the key to the group’s biggest successes and its greatest mystery. Not long after joining Bell Labs, Schön flew from New Jersey to Konstanz to finish up work on his Ph.D. “I got back to Konstanz and was sputtering aluminum oxide for solar-cell coatings,” he recalled in February. “No one else was using the machine, so I decided to try it out” for the organic transistors. The machine coated the organic crystals with a neat insulating layer.

Later, Schön used a low-temperature scheme to deposit the gate electrode on top of the aluminum oxide while protecting the fragile organics. When he hooked up the electrodes to a power supply and flipped the switch, he recalled later, the results jumped off the screen. Not only had the fragile organic crystals not cracked, broken, or turned to ashes, but they had changed from insulators to semiconductors, conducting current when prompted by the gate voltage.

The result was a paper published in the 11 February 2000 issue of Science (p. 1022). “That was the first time the community took notice of the crystals,” Batlogg said.

The paper caused a sensation in the condensed-matter physics community, because it held out the prospect that researchers could make electronic devices out of an enormous variety of organic materials. Those wouldn’t necessarily be any better than silicon FETs for computer circuitry. But they would give researchers a new way to track how electrical charges move through a wide variety of materials. According to the Institute for Scientific Information, the paper has since been cited 130 times, making it not only Schön’s most highly cited paper but also one of the top 0.01% of all physics papers published in 2000.

Schön, Batlogg, and Kloc were just getting warmed up. And Stormer was ready with a new challenge. “Horst said, ‘Any real semiconductor has a quantum Hall effect,’” Batlogg noted. The effect, a stepwise change in voltage that occurs when a semiconductor studied with electrodes is placed in a magnetic field, is a hallmark of the quantum-mechanical behavior of electrons. Most physicists thought it could be observed only in materials so pure that electrons move through them without scattering off obstacles. Because organic crystals normally harbor so many impurities, “I never thought we’d see it,” Schön said.

But, on 23 December 1999, just before taking off to Germany for the holidays, Schön ran the experiment and reported seeing the telltale voltage steps. “We showed the result to our [Bell Labs] colleagues, and everyone thought we were joking,” Batlogg said. Added Schön: “It was a nice Christmas present.” Later, Schön also noted that he had witnessed a related effect called the fractional quantum Hall effect, the effect for which Stormer had shared his Nobel Prize in 1998. “Wow. I thought this was fantastic,” Stormer recalled in an interview a week before news of the disputed figures broke.

Superconductors and beyond

The Bell Labs trio didn’t revel in its success for long. By now, Kloc was churning out high-quality crystals of a variety of organics, including ones made of C60, the soccerball-shaped carbon molecule also known as a
buckyball or buckminsterfullerene. Back in 1991, a Bell Labs team that included Ramirez had turned the normally insulating C₆₀ into a superconductor by spiking it with potassium atoms. The potassiuums harbor extra electrons, which could move around through the crystal and pair up as they go, a signature of superconductivity. Theoretical results suggested that if researchers could add three extra electrons for each C₆₀ molecule in the crystal, they could get it to superconduct without potassium atoms.

Where to get those electrons? Schön, Batlogg, and Kloc wondered whether they could use the electric fields produced by their FETs to yank them from the FET electrodes and shunt them into a channel made from C₆₀. If the density of charges got high enough, perhaps the material would resemble a metal like copper, or, if they got really lucky, perhaps even a superconductor.

But that wasn’t a simple proposition. The density of free electrons in a metal is at least 1000 times that of a semiconductor. “If you want to go to very high [electron] concentrations, you have to apply a very high field” to the gate electrode, Schön said. Normally, that turns the organic to ash. So Schön needed not only to build FETs atop C₆₀ but also to have the organics and the aluminum oxide insulator withstand withering electric fields. Nearly all his attempts failed. But in a few cases, Schön’s seemingly magic layer of aluminum oxide somehow handled the high currents. In the 28 April 2000 issue of Science (p. 656), Schön and his colleagues reported that they had coaxed potassium-free crystals of C₆₀ to superconduct at 11 degrees above absolute zero.

Not bad for starters. But they dreamed of achieving even higher superconducting temperatures. Theorists had suggested that C₆₀ could reach such temperatures if it could be made to conduct positively charged “holes” instead of electrons. Holes are vacant electron sites and can move through a material just as electrons do. But, although chemists could add extra electron-carrying atoms such as potassium into a C₆₀ crystal, there was no chemical method for adding holes.

FETs, however, can manage the task handily. All the researchers had to do was simply reverse the polarity on the electrodes to pull electrons off the C₆₀’s. In the 30 November issue of Nature, Schön, Batlogg, and Kloc reported that the scheme worked just as theory said it should, allowing a C₆₀ crystal to superconduct at 52 kelvin. Less than a year later, they reported in Science that they had tweaked the C₆₀ crystals to push the superconducting temperature up to 117 K (Science, 31 August 2001, p. 1570).

The papers not only shattered the record for superconductivity in C₆₀ but also offered researchers the heady prospect of finding high-temperature superconductors without painstakingly doping each material with different impurities. “They defeated chemistry,” Princeton University physicist Bob Cava said in February.

More marvels were to come. In 2000 and 2001, papers by the trio were flooding the journals. Schön and collaborators both inside and outside of Bell Labs reported turning organics into everything from light-emitting lasers to light-absorbing photovoltaic devices. They made plastic, a notoriously messy organic compound, superconducting. And they showed that their high-field FETs could work just as well with inorganic superconductors, a development that promised to revolutionize the field of high-temperature superconductivity.

As if that weren’t enough, while Schön was rewriting the textbooks on condensed-matter physics, he was also busy pioneering a separate field: molecular-scale transistors. In the 18 October 2001 issue of Nature, he and Bell Labs colleagues Zhenan Bao and Hong Meng reported making a novel type of transistor in which the key charge-conducting layer was composed of a single layer of an organic conductor. They followed that with a report in the 7 December issue of Science (p. 2138) describing how they diluted the charge-conducting layer with nonconducting insulating molecules, allowing them to track the conductivity in a transistor through a single molecule. Together, the results were hailed as a triumph of molecular-scale electronics.

Through the beginning of this year, Schön had racked up 15 papers in Science and Nature, as well as dozens in other journals. Between 1998 and May 2002, he published more than 90 papers and was lead author on 74 of them, a staggering level of productivity. Of his top 20 papers, all are in the top 10% of physics papers for their number of citations, with eight in the top 0.1% (see table). Many of those citations are no doubt Schön and colleagues citing their own previous work. Nevertheless, the work clearly captured the imagination of others in the community. “Hendrik has magic hands,” Ramirez said in the March interview. “Everything he does seems to work.”

But, even before the revelations in May, questions began to swirl around Schön’s work. His magic, other researchers noted nervously, didn’t seem to work for anyone else. Over the past 2 years, efforts to slap high-field FETs on different materials have become one of the hottest endeavors in condensed-matter physics. The U.S. Department of Energy, for example, has helped fund a new group specifically to try to reproduce and extend the Bell Labs results.

So far, however, the well is dry. “It’s very

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**SCHÖN’S TOP TEN**

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<th>Topic</th>
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*Ranking among the top percentage of all physics papers in the same year by number of citations, as determined by the Institute for Scientific Information. Red: Implicated in possible data duplication. Black: Not suspected of duplication.*
unusual to have a result that is 2 years old that hasn’t been reproduced,” Richard Green, a physicist at the University of Maryland, College Park, said during an interview in February. Added Robert Dynes, a physicist and chancellor of the University of California, San Diego: “Some people are frustrated and discouraged.”

Some researchers also complain that Schön’s early papers left out key details needed to reproduce the work. “There is an uneasy feeling around the community,” said Teun Klapwijk, a physicist at the Delft University of Technology in the Netherlands on 2 May, just before the discovery of the apparent duplication of data. “Why do the papers have so little detail? It’s such a unique case of a whole string of papers where each paper shows you the beautiful result you want to see: the Hall effect, lasing, the quantum Hall effect, superconductivity. People kept feeling, ‘Is that possible? How do you produce so many results? Is that physically possible?’”

Much of the concern boiled down to Schön’s aluminum oxide. Making the electron barrier is a piece of cake. You just vaporize the materials in an apparatus called a sputtering machine and let the vapor rain down on your sample. Add the electrodes, and you’re in business. “You really need very little to get into the game,” said Ramirez. But when most researchers start turning up the electric fields to drive electrical charges into their organic materials, they can create fields of only about 10 million volts per centimeter before the aluminum oxide starts to bubble, turn black, and vaporize, taking the fragile organic materials with it. Somehow, Schön’s aluminum oxide gets up to 45 million volts/cm—nearly five times higher than anyone else. “What is the trick?” asked physicist Arthur Hebard of the University of Florida, Gainesville. IBM physicist John Kirtley agreed: “That’s the $64 million question.”

**Magic box**

In an interview last February, Schön, Batlogg, and Kloc said they were as eager to find out the answer as everyone else. “I wish we knew,” Batlogg said. Added Schön: “If we knew, then we wouldn’t have to waste 18 samples out of 20.” Schön said he had looked at the aluminum oxide layers under ultrahigh magnification but found nothing remarkable—just a noncrystalline amorphous layer of aluminum oxide. Whatever the secret, it seems unique to Bucher’s sputtering machine in Konstanz, the only place where Schön has managed to grow aluminum oxide layers that withstand the high fields.

Sputtering machines are commonplace in the world of semiconductor electronics, and Bucher’s is a run-of-the-mill one at best. The machines vaporize their targets in a vacuum to ensure that outside compounds don’t find their way onto a sample. But the vacuum in Bucher’s machine is “lousy,” said one researcher, capable of reaching a pressure of 10⁻⁶ torr. By contrast, state-of-the-art molecular-beam epitaxial machines—devices used to lay down vaporized materials one atomic layer at a time—can reach 10⁻¹² torr.

The upshot, says one researcher, is that Bucher’s machine isn’t just laying down aluminum oxide: “It has everything in it—your breath, water, other gases.” That rain of mystery compounds, the Bell trio speculates, might somehow toughen the material against meltdowns, perhaps by plugging defects that would otherwise snag electrical charges.

Even if other groups manage to make aluminum oxide that’s stable in high electric fields, high-field FETs will face further hurdles. For the devices to work, both the underlying crystals and the interfaces between the different layers of semiconductors, insulators, and metals need to be nearly perfect to prevent charges from getting hung up as they travel between layers and burning out the device. As a result, Texas’s Dodabalapur said at a meeting of the American Chemical Society (ACS) in April, high-field FETs are so fragile that getting them to work “requires the skill of a jeweler, the persistence of a saint, and the background of a physicist.”

Even so, some teams believe they’re making progress. Ramirez’s group at Los Alamos has made the most headway. At the March meeting of the American Physical Society in Indianapolis, Indiana, Ramirez reported that when he and colleagues ran currents through FETs they had created using C₆₀ crystals made by Kloc, they saw signs of the organic’s behaving like a metal—although not a superconductor.

**Clou ded prospects**

That was where Schön’s saga stood in early May. Since then, the latest chapter—revelations of possible duplication of data—has cast doubt on all that went before. It would make matters far simpler if Schön could submit his best FETs for independent testing or invite other researchers to make measurements on his equipment. But that’s not possible. The small fraction of Schön’s FETs that did work in the past were either fried in the process or have degraded, he says. Worse, Schön’s magic in making his high-strength aluminum oxide seems to have evaporated, as even he has been unable to reach the high electric fields for about the last 6 months. “We have the same problems now as everyone else,” Schön said at the April ACS meeting. “It has been frustrating. We can empathize with what others have been going through.”

Now, one of the most exciting strings of results in modern physics is under a cloud. It’s impossible to say which work will stand the tests of time and intense scrutiny. “Maybe some of the most dramatic stuff is right,” says James Heath, who heads the California NanoSystems Institute at the University of California, Los Angeles. “What’s harder to believe: that everything is wrong, and they made up all of the data, or that some of it is real? It’s easier to believe that there are some legitimate results.”

If Schön’s results hold up, they would point the way to exciting physics and novel devices. If not, the loss could be devastating—not just for the careers of those directly involved but for the credibility of Bell Labs, condensed-matter physics, and science as a whole. Research on organic electronics would of course press on. But, it would march less resplendently than it did before Hendrik Schön set foot in Bell Labs 4 years ago.

—ROBERT F. SERVICE
Pioneering Physics Papers Under Suspect for Data Manipulation

Recent discoveries at Bell Laboratories—the research arm of Lucent Technologies in Murray Hill, New Jersey—said to be of Nobel quality suddenly became mired in questions last week. Outside researchers presented evidence to Bell Labs management on 10 May suggesting possible manipulation of data involving five papers published in Science, Nature, and Applied Physics Letters over 2 years. In response, Bell Labs officials said that they are forming a committee of independent researchers to investigate. Their conclusions may not be known for months, but scientists who have seen the data are already saying that the potential fallout from the investigation could be devastating.

The Bell Labs papers describe a series of experiments with organic conductors, but portions of the figures appear almost identical, according to the physicists who raised suspicions. Particularly puzzling, they say, is the fact that two graphs show a pattern of “noise” that looks identical, although it should vary randomly.

Bell Labs physicist Jan Hendrik Schön is lead author on the papers in question and the only author whose name appears on all five. Among his most frequent co-authors are two colleagues from Murray Hill, Bertram Batlogg—a former Bell Labs physicist who has since moved to the Swiss Federal Institute of Technology in Zurich—and Bell Labs chemist Christian Kloc. Schön told Science he stands behind his data and says it’s not surprising that experiments with similar devices produce similar-looking data. “We are trying as hard as we can to repeat those measurements,” Schön says. “I am convinced they will show I haven’t done anything wrong.” Co-authors on the five papers either declined public comment or could not be reached.

Many scientists have reacted with disbelief. “I’m shocked,” says James Heath, a chemist at the University of California, Los Angeles, and director of the California NanoSystems Institute: “It’s hard to understand. I know these people. Most of them are good, careful scientists.” “It’s a little overwhelming,” adds Lydia Sohn, a Princeton University physicist who helped bring some of the discrepancies to light. “It’s just disturbing, and disappointing, and sad.” The noise pattern is particularly disturbing, says Charles Lieber, a chemist and nanoscience expert at Harvard University in Cambridge, Massachusetts: “It’s virtually impossible for me to believe that some of this wasn’t made up.”

Schön himself acknowledges that the similar noise pattern is “difficult to explain.” But others affiliated with Bell Labs suggest privately that a systematic artifact in the measurement equipment might account for the similar noise trace, and that in the other cases, computer files containing similar data could have been mixed up.

Still, Lieber and others say the concerns are so serious that the authors should immediately withdraw the papers in question. “They should be retracted until they can be duplicated,” Lieber says. But Cherry Murray, who heads physical sciences research at Bell Labs, says the company won’t take any action until the external review committee reaches its conclusion. “We are not rushing to judgment,” Murray adds. Science’s editor-in-chief, Donald Kennedy, says that’s the right course of action. “Until one completes an investigation, it’s premature to make any decisions about the papers,” he says.

Until last week, most physicists viewed Schön and his collaborators with something between envy and awe. Schön joined Bell Labs as a postdoc in 1998 to work with Batlogg and Kloc, setting out to study the way electrical charges conduct through organic crystals. They soon propelled Bell Labs beyond all competition in the nascent field of organic transistor research.

In a series of groundbreaking papers—most of which are not directly implicated in the current inquiry—the researchers showed that they could use devices called field effect transistors (FETs) to inject large numbers of electrical charges into organic materials. By changing the concentration of charges, they could tune the electronic properties of the materials to behave in any number of ways—as an insulator or semiconductor, or a metal or superconductor—exhibiting a malleability that had never been seen before.

The group also reported that organic FETs displayed superconductivity at a temperature higher than had ever been seen in an organic material, revealed quantum signatures never before seen in organics, and could be made to act as lasers and novel superconducting switches. Physicist Art Ramirez of Los Alamos National Laboratory in New Mexico, praising the work in an interview prior to the recent revelations, says “the string of papers is really outrageous” in its success. “I don’t know of anything like it.” Heath says he was equally impressed: “I saw Batlogg talk about [the team’s results] a year ago at a meeting in Venice. I was blown out of my chair. I thought, ‘These guys are going to Stockholm.’”

The astounding results prompted groups around the world to attempt to replicate the work. But to date, although other researchers have made some progress, no one has reported duplicating any of the high-profile results. That troubled many in the community, says Cornell University physicist Paul McEuen, the first to notice the apparent duplication of data.

Some physicists grew more concerned last fall when Schön published a pair of papers on a different topic in Nature and Science with Bell Labs colleagues Hong Meng and Zhenan Bao. In the first, published in the 18 October 2001 issue of Nature, the researchers reported making a novel type of transistor in which the key charge-
conducting layer was composed of a single layer of an organic conductor. In the Science paper, published in the 7 December issue (p. 2138), they reported diluting that charge-conducting layer with nonconducting insulating molecules, allowing them to track the electrical conductivity in a transistor through a single molecule. Together, the results received international press attention as a triumph of molecular-scale electronics. But McEuen says the papers puzzled researchers because, despite the novel architecture of the devices, they seemed to conduct current in a manner similar to traditional FETs.

Last month, a more troubling aspect came to light: Researchers noted that figures describing the conductivity in the two papers appeared identical, even though the measurements were supposedly done at temperatures different enough to affect the results. According to Princeton’s Sohn, several Bell Labs researchers pointed out the identical figures to her, McEuen, and others. “Collectively, people at Bell [Labs] were nervous,” says Sohn, although she declines to identify who tipped her off. Word of the duplicate figures began to spread. And late last month, Lieber and Harvard physicist Charles Marcus contacted manuscript editors at Science and Nature informing them of the apparent problem.

A few days later, even before he had heard from Science, Schön e-mailed Science associate editor Ian Osbourne to say there had been a mix-up and that the wrong figure had mistakenly been incorporated in the Science paper. Schön also sent along a new figure, which appears as a correction on page 1400 of this issue.

But Sohn says the mix-up explanation just didn’t sit well with her or McEuen. “Paul said, ‘Lydia, I’m just going to look at the data, the figures,’” says Sohn. And on Thursday, 9 May, McEuen stayed up much of the night looking through Schön’s Science and Nature papers and found what he calls two “disturbing” coincidences.

The first involves the same duplicate figures that prompted the heads-up from Lieber and Marcus. McEuen noticed a close resemblance with yet another figure, this one in the 11 February 2000 issue of Science (see figures above). The figures show how changes in an electrical voltage applied to a control electrode called a gate alter the ability of charges to conduct through a simple circuit of two FETs. The devices in the 11 February 2000 Science paper reportedly contain different materials in the key charge-conducting channel in each FET and a different physical geometry, both of which should cause these devices to conduct current differently from devices described in the other papers, says McEuen. But when McEuen resized the figures and overlaid the data, he found that the seemingly uninteresting background data on the right portion of the figures looked similar. “The noise looks almost identical, bumps and all,” McEuen says. “This is very confusing and disturbing. They should be vaguely similar, maybe roughly similar. But certainly the noise shouldn’t be the same,” McEuen says. “This knocked me for a loop.”

He quickly got another shock. McEuen noticed that the same 11 February 2000 Science and 18 October 2001 Nature papers contained another similar figure, which also closely resembled a figure in a third paper, from the 28 April 2000 issue of Science. All three papers describe different organic conductors. Yet, if one ignores the labels, several of the data traces appear very similar. “There is no physical reason why they should be similar,” McEuen says.

The next day, 10 May, McEuen says he and Sohn were concerned enough that they contacted Schön, Batlogg, managers at Bell Labs, and manuscript editors at Science and Nature. He says that all involved expressed deep concern.

A couple of days later, Sohn found another uncomfortable coincidence. In this case, six data traces in a figure in the 3 November 2000 issue of Science appear virtually identical to ones in the 4 December 2000 issue of Applied Physics Letters (APL). But, whereas the Science paper tracked the conductivity of a light-emitting organic material known as α-6T in a FET, the APL paper followed the conductivity in a non–light-emitting FET made with an organic compound called perylene. Moreover, whereas the FETs in the α-6T figure are “n-channel” devices, which conduct negatively charged electrons, those in the perylene figure are “p-channel” devices, which conduct positive charges. According to McEuen, most physicists believe that should cause the devices to conduct current in a slightly different manner. “They overlap, noise and all,” says McEuen. “They are identical,” except that the labels on the axes referring to the voltages applied to the devices have an opposite sign, he adds.

Taken together, the three examples are deeply troubling, says Leo Kouwenhoven, a physicist at Delft University of Technology in the Netherlands. “I think that it is very worrisome,” Kouwenhoven says. “I can imagine you switch one figure by mistake. It’s hard to imagine how you switch 10 figures.” Schön says that because his papers report the conductivity in FETs, “I would expect them to be very similar.” He declines to comment on other specific issues. Bell Labs’ Murray declines to comment on specifics as well, but adds: “I am very concerned. … This deserves a full and complete investigation.”

A five-member committee headed by Stanford University physicist Malcolm Beasley began an investigation last Friday. Beasley says he cannot estimate how long it will take or whether it will be broadened to look at data presented in other papers. Schön has been the first author on 17 papers in Science and Nature alone in the last 2.5 years and a co-author on dozens elsewhere. Beasley says: “We are hoping for something by the end of summer.”

McEuen, for one, believes Bell Labs is taking the proper first step. “Beasley has great stature in the community. … Everybody wants to get to the truth.”

—ROBERT F. SERVICE
XVIII. Unrealistic Precision: Characterization of sputtering process

Allegation

Many questions have been raised about why the breakdown strength of Hendrik Schön’s sputtered Al₂O₃ was so much greater than others have been able to achieve. Values up to 70-80 MV/cm (at low temperatures) are implicit in some of the field-induced superconductivity data; for the “Sputtering” Paper a mean of 23 MV/cm was indicated at room temperature. As reported to the Committee, various recent attempts to reproduce Hendrik Schön’s results have so far been limited at 12 – 15 MV/cm, including work at the University of Konstanz using the same sputtering system used by Hendrik Schön in most of the work in question. In the “Sputtering” Paper Hendrik Schön provides evidence that the mean breakdown strength increases from 23 MV/cm at room temperature to 32 MV/cm at 220 K.

Reportedly, Hendrik Schön was strongly encouraged by Bertram Batlogg, his management, and external scientists to document the processing conditions and optimization of his Al₂O₃ gate insulators, to enable the reproduction of these results. The result is the unpublished “Sputtering” Paper (XXIV), included in the materials provided to the Committee by Bell Labs. This document was distributed in preprint form, and also submitted for publication. It has received wide circulation in the community, and for this reason it was judged appropriate for consideration by the Committee along with published papers. This document shows a level of statistical precision that is virtually unheard of in processing experiments, and in any event inconsistent with the reported size of the data set.
Appendix E: Elaborated Final List of Allegations

Figure 2 of the “Sputtering” Paper (XXIV) is a histogram of breakdown fields for a particular set of processing conditions within the “sweet spot” claimed by Hendrik Schön (see below). The line shows a best-fit Gaussian model. This Gaussian fit yields a mean breakdown field of 23.8 MV/cm and a standard deviation of 6.04 MV/cm. The data set includes over 600 samples, reportedly deposited and measured episodically over several years.

There are several problems with these data. First, a Gaussian distribution is not expected. More typical breakdown data show many points clustered at the true, intrinsic breakdown and a tail at lower breakdown fields, described by a Weibull distribution. Nonetheless, the agreement with the Gaussian distribution is excellent. Indeed, the $\chi^2$ for these data is about 0.41; a simple estimate of the probability of such good agreement arising from chance for the reported sample size of 600 is about 0.02%.

According to the histogram, one can get the very highest fields implied by the experiments only by operating at the extreme high end of the breakdown distribution, accepting the resultant low yield. If the distribution were tighter, or skewed to low breakdowns, or there were no increase at low temperatures, these high breakdown fields would not be available. Hendrik Schön stated that if he did not observe superconductivity after a few tries, he would move on to something else.
Figure 54 shows a contour plot of the breakdown field as a function of two process variables: deposition rate and pressure. For those familiar with process studies and contour plots, it is extraordinary to see such a plot. Such smooth contours are not possible unless the “z axis” data are very precisely specified, and process studies are usually difficult to reproduce with precision, especially on typical research equipment. (In this case, Hendrik Schön claims that this was “not a systematic study,” but simply a compilation of data taken over a period of several years; this makes the extraordinary reproducibility even more surprising.) One purpose of this plot is to illustrate the small “sweet spot” of the deposition near 0.02 nm/s deposition rate and 5 mbar pressure.

This plot contains a dense array of points at twelve deposition rates and twelve pressures, including a large section of parameter space where the films are not very good. Consequently, there are 144 different deposition conditions specified. In each case, the signal-to-noise of the breakdown is very high. As illustrated in the Figure 55 (a slice of...
Appendix E: Elaborated Final List of Allegations

the above contour plot), the scatter appears to be less than 1MV/cm. Thus this figure requires a total of 36x144=5,184 breakdown measurements to be made. (To obtain the mean breakdown field to a precision of 1MV/cm requires roughly 36 measurements (6MV/cm / 1MV/cm)^2, because of the 6 MV/cm standard deviation of the breakdown field).

The paper says that 150 samples were made at each of 36 conditions, also more than 5000 measurements. Most of them contribute little to the information about the process optimum. The phenomenal effort required to create this data, together with the fact that deposition systems do not as a rule behave this reproducibly, is the reason most process studies have just a few points.

For completeness, some caveats in the paper include the possibility that the breakdown criteria used here are more tolerant than in traditional breakdown studies, and the possibility of some history effect in the chamber.

Finally, this preprint also contains an illustration of field-induced superconductivity involving sweeping the gate voltage up and then down (see Figure 56). Detailed examination (from the original plotting data in the electronic draft) shows that the sweep up and down are the same data to six significant figures, precisely reflected around the maximum field.

Response

Hendrik Schön supplied voluminous documentation describing the results of the breakdown studies. He was not able to explain the statistical anomalies. The description of some of the aspects of the breakdown measurement have changed during revision. For
example, it was noted by Bertram Batlogg (in email to Hendrik Schön) that the breakdown measurements in Figure 54 would have taken 2.4 years, using the sweep rates stated in an early version of the preprint. The sweep rate in the paper was subsequently modified from 0.001 V/s to 1 V/s. According to Hendrik Schön and the documentation provided, the actual process matrix was 6x6, and the 12x12 points in the contour plot were created by smoothing and interpolation. No justification was offered for this information-destroying procedure, except “to give a nicer contour plot.” Surprisingly, this smoothing and interpolation procedure did not reduce the excellent breakdown field at the “sweet spot” (compare the blue squares in Figure 55 to the other symbols).

Included in the documentation Hendrik Schön provided to the Committee was a tabulation of the breakdown fields of all 150 samples for each of the 36 deposition conditions represented in the contour plot. Not one of the 5400 measurements indicated a breakdown field less than 3.7 MV/cm.

When presented with the details of symmetry of the field sweep demonstration of superconductivity, Hendrik Schön acknowledged that the data had been artificially symmetrized.

Conclusion

The data presented in this preprint are so statistically improbable that it seems impossible that they represent real data, free of some selection process or some other misrepresentation.

The wide distribution of this preprint among scientists in this field is considered by the Committee to be tantamount to publication. The preponderance of evidence indicates that Hendrik Schön committed scientific misconduct, specifically data fabrication, in this case.
Bell Labs Fires Star Physicist

Found Guilty of Forging Data

Like the mythical Icarus, whose waxen wings melted when he flew too close to the sun, the soaring career of Jan Hendrik Schön came crashing down to Earth last week. Schön, a 32-year-old physicist at Bell Laboratories in Murray Hill, New Jersey, faked experimental results in at least 17 published papers, according to a report released 25 September by a panel of independent investigators. Schön had been fired from Bell Labs the previous evening, after officials there received the report. The findings mark this as one of the most extensive cases of scientific misconduct in modern history and signal a low-water mark for Bell Labs, an institution already reeling from economic troubles of its parent company, Lucent Technologies.

“It’s a big train wreck and very sad,” says Lydia Sohn, a Princeton University physicist who was one of the first to point out Schön’s apparent manipulation of data. “But this shows that the system of checks and balances in science works.” Others were less consoled. “If this guy [had been] a little less blatant, he could have succeeded. That’s the terrifying thing,” says Paul McEuen, a physicist at Cornell University in Ithaca, New York.

The panel cleared Schön’s co-authors of any direct scientific misconduct. But it left open questions that are likely to reverberate through scientific circles for years to come. Chief among them are whether papers Schön co-authored that were not reviewed by the committee are valid and whether Schön’s co-authors, the journals that published his papers, or scientific referees should have caught the fraud earlier. “There are other questions, and they are for others to address,” says Stanford University physicist Malcolm Beasley, who chaired the panel.

Bell Labs hired Schön as a postdoctoral researcher in 1998 to work with Bertram Batlogg—then Bell’s head of solid state physics research—on investigating how electrical charges move through crystals of organic semiconductors. Working with crystal growers Christian Kloc, Schön and Batlogg made rapid progress. Early on, they reported a new way to inject large electric currents into their organic crystals. That advance produced an extraordinary string of effects, including superconductivity, the fractional quantum Hall effect, and laserlike behavior. “He rediscovered everything in condensed matter physics in the last 60 years” in organic materials, Sohn says.

In his 4-year career at Bell Labs, Schön’s steady stream of stunning breakthroughs promised to revolutionize the fields of organic electronics, superconductivity, and nanotechnology. By the beginning of this year he had produced a string of more than 90 papers, most of which listed him as the lead author. In 2001, Schön churned out a new paper on average every 8 days, a level of productivity nearly unheard of in physics.

To researchers watching from the wings, Schön seemed to be a Tiger Woods of physics, a young prodigy overwhelming the competition. “These papers came out and you’d say, ‘Oh, no,’” recalls Arthur Ramirez, a physicist at Los Alamos National Laboratory in New Mexico. “It would be a monthly demonstration of how stupid you are. He was creating a new field every 2 months.”

Late last year, two of Schön’s break-
scientific claims. “The evidence that manipulation and misrepresentation of data occurred is compelling,” the report concludes.

Despite repeated attempts, Schön could not be reached for comment. But in a response included in the report, Schön said, “I have to admit that I made various mistakes in my scientific work, which I deeply regret … However, I would like to state that all of the scientific publications that I prepared were based on experimental observations.” Schön apologized for his mistakes but added that he was confident that the underlying physical effects are “real, exciting, and worth working for.” In a telephone interview the week before the report’s release, Schön said he had been trying all summer to confirm his earlier results, but to no avail.

The Beasley committee found no evidence of misconduct by any of Schön’s co-authors. But the report raises pointed questions about the role of Batlogg, Schön’s initial supervisor, who left Bell Labs last year to become a professor at the Swiss Federal Institute of Technology in Zürich. It asks, “Should Batlogg have insisted on an exceptional degree of validation of the data in anticipation of the scrutiny that a senior scientist knows such extraordinary results would surely receive?” Says Beasley about the responsibility of co-authors: “That’s a very difficult issue and one that the scientific community has not thought deeply about.”

Few other researchers seem ready to let the matter rest there. “Batlogg was certainly happy to bask in the glow when things looked wonderful. But you can’t have it both ways and not accept some level of the burden of responsibility,” says one physicist who asked not to be identified. Ramirez agrees. “This is something he is trying to wash his hands of, and I don’t like it,” he says. “It’s really tragic. He’s had 25 years of research. He’s lost that standing. He’s going to have to work hard to regain a level of credibility.”

Batlogg acknowledges that he should have done more to confirm the accuracy of the papers he co-authored. “I have learned, with the deepest of regrets, that the verification measures I have followed in this extraordinary case were not adequate to prevent or uncover scientific misconduct,” he wrote in an e-mail message to Science. He says he plans to redouble checking procedures in the future but that “trust in colleagues shall and must remain one of the foundations on which we build future research endeavors.”

Other critics are equally hard on higher-ups at Bell Labs. “They should have said, on papers before they are sent out for publication, in hopes of ferreting out dubious science before it is made public.

Perhaps the biggest question the report leaves hanging is the fate of Schön’s papers. Murray says that Bell Labs management is working with the authors to submit retractions for the papers that were red-flagged by the committee. But that could be difficult. Donald Kennedy, editor-in-chief of Science, notes that all of a paper’s authors must agree for Science to issue an retraction. “We have been in continuing discussion with the Bell Labs leadership to bring that about promptly for each paper,” Kennedy says. “We have also agreed that if those efforts fail, we will invite co-authors to issue their own statements and publish them together with an editorial announcement of Science’s position with respect to each paper.”

Nature’s head physical sciences editor, Karl Ziemelis, says Nature might not wait for the authors to act. “It’s absolutely clear, given the verdict of the panel, that the papers need to be retracted,” Ziemelis says. “But if that doesn’t happen quickly, we almost definitely will take other actions,” such as publishing a notice to readers informing them of the committee report and its specific conclusions involving Nature papers, Ziemelis says. He adds that Nature will invite Schön and his colleagues to retract two other Nature papers not reviewed by the committee.

Retractions are unlikely to allay widespread concerns among physicists that journals gave some of Schön’s papers expedited treatment in their eagerness to publish the sensational results. But both Ziemelis and Science’s lead physical sciences editor, Phillip Szuromi, say that thorough reviews of the referee reports show that wasn’t the case. “The referee reports weren’t supporting rejecting the papers,” Szorumi says. Nature’s referees did raise questions about some of the papers Nature published, Ziemelis says, but those centered almost exclusively on the interpretation of the results. “What was almost unanimous was overall praise for the data presented in the papers,” he says.

Now, researchers are likely to treat all of Schön’s data as suspect. Many say they have no choice but to stop citing any paper bearing Schön’s name, to maintain their own credibility. “For me this [misconduct] basically invalidates the whole body of work,” Ramirez says. Adds McEuen: “I’m just pretending that the work doesn’t exist. Actually I don’t have to pretend. It doesn’t.”

—ROBERT F. SERVICE