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For more than two years, condensed matter physicists were enthralled by results coming out of Bell Labs, Lucent Technologies, where researchers had developed a technique to make organic materials behave in amazing new ways: as superconductors, as lasers, as Josephson junctions, and as single-molecule transistors. (PHYSICS TODAY ran news stories on some of these topics in May 2000, page 23; September 2000, page 17; January 2001, page 15; and October 2001, page 19.) Increasingly, however, enthusiasm gave way to frustration, as research groups were unable to reproduce the results. Was the technique exceedingly difficult to master, or was something else amiss?

Last spring, red flags went up. Physicists from inside and outside Bell Labs called management's attention to several sets of figures, published in different papers, that bore suspiciously strong similarities to one another (see PHYSICS TODAY, July 2002, page 15). Much of the suspicion focused on Jan Hendrik Schön, a key participant in the research and the one author common to all the papers in question. With a few exceptions, Schön had applied crucial aluminum oxide insulating layers to the devices, had made the physical measurements, and had written the papers. Moreover, the sputtering machine that Schön used to apply the Al_2O_3 films was located, not at Bell Labs, but in his former PhD lab at the University of Konstanz in Germany.

According to Cherry Ann Murray, director of physical science research at Bell Labs, management had been made aware of some problems with Schön's work in the autumn of 2001, but at the time attributed the problems to sloppiness and poor record-keeping, not fraud. After learning this past spring about the similar-looking figures, Bell Labs management convened a committee to investigate the matter. Malcolm Beasley of Stanford University headed the committee; serving with him were Supriyo Datta of Purdue University, Herwig Kogelnik of Bell Labs, Herbert Kroemer of the University of California, Santa Barbara, and Donald Monroe of Agere Systems, a spinoff of Lucent.

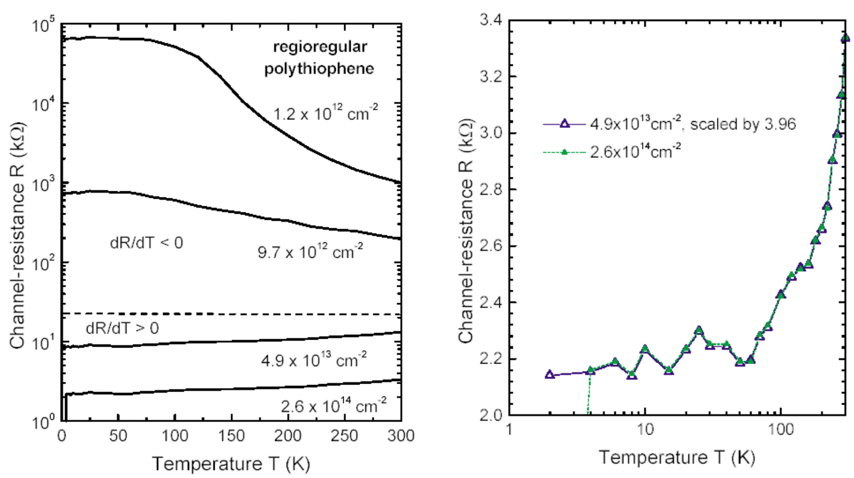
Bell Labs released the committee's 127-page report in late September.[1] The committee had examined 24 allegations (involving 25 papers) and concluded that Schön had committed scientific misconduct in 16 of those cases. "The evidence that manipulation and misrepresentation of data occurred is compelling," the report concluded. The committee also found that six of the remaining eight allegations were "troubling" but "did not provide compelling evidence" of wrongdoing. Bell Labs immediately fired Schön.

Detective work

To reach its conclusions, the investigative committee had to do a bit of digging. Schön no longer had his primary electronic data files, claiming that he had deleted them for lack of sufficient storage on his old computer. Nor did he have any working devices on which tests might be run; they had been destroyed in measurement or in transport, or thrown out. Even the sputtering machine at Konstanz was no longer producing films with the required high breakdown strengths. Nevertheless, Bell Labs provided the committee with some data files that had been embedded in early electronic drafts of papers or in presentation files.

The committee classified each allegation as one of three types: substitution of data, unrealistic precision, or contradictory physics. An example of the first is shown in the figure below. The left-hand panel reproduces a figure from a paper reporting gate-induced superconductivity in polythiophene.[2] It shows how the resistance of polythiophene decreases as the surface carrier density (which is controlled by a gate voltage) increases until the material goes superconducting at a density of $2.6 \times 10^{14}/cm^2$. Using the plotting data contained in an early draft, the committee found that the data for the two highest densities differ only by a constant multiple of 3.96, except for a single point below the superconducting transition temperature (see the right-hand panel).

One of the papers alleged to have reported unrealistic precision is an unpublished but widely circulated preprint by Schön that describes his technique for sputtering thin films.



DATA SUBSTITUTION was found in a paper describing gate-induced superconductivity in polythiophene.[2] The published figure (left panel) shows resistance for four values of surface charge density. Superconductivity sets in at the highest density. The bottom two curves are replotted in the right panel, with the curve for a density of $4.9 \times 10^{13}/cm^2$ divided by 3.96. An investigation found that the data were the same, except for one point. (Reproduced from ref. 1.)

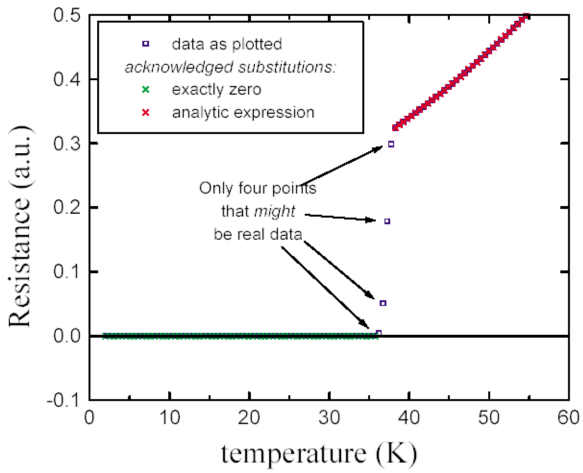
The paper was intensely studied by those who were trying to achieve very high breakdown strengths at low temperatures; it's estimated that one needs fields as high as 80 MV/cm to get the field-effect superconductivity that's been reported. The committee judged that the data in that preprint had "a level of statistical precision that is virtually unheard of in processing experiments." To get that precision would require 5000 measurements. The voltage distribution displayed an excellent fit to a Gaussian, even though another form was expected.

The distribution was centered on 23 MV/cm, implying a very low yield for samples with breakdown strengths as high as 80 MV/cm. Even so, 23 MV/cm exceeds the values of about 15 MV/cm achieved by researchers like Arthur Ramirez of Los Alamos National Laboratory, who are trying to reproduce the Bell Labs results.

As one allegation of contradictory physics, the committee cited figure 1 from a paper[3] reporting the superconductivity of hole-doped carbon-60. The committee enlarged one of 20 curves in the original figure; it shows the temperature-dependent resistance of a sample for one particular value of gate voltage (see the figure on this page). The transition seen is much sharper than one would expect for the virtually two-dimensional surface layer involved in this experiment, reported the committee; one would expect a much broader transition. It turns out that most of the data are not real. In response to another allegation, Schön admitted having substituted an analytic curve for real data above the transition temperature, although, he asserted, the transitions really had been measured. "I felt that a smoother curve would look much better," Schön told the committee.

The extent and depth of the misconduct ferreted out by the committee stunned Lydia Sohn (Princeton University) and Paul McEuen (Cornell University), two of those who had initially raised questions about the work. Although McEuen had uncovered evidence that some curves had been substituted for others, he knew nothing about fabricated data, he said. "I was shocked that there was this other layer of stuff."

The committee noted that Schön, "with only one exception . . . did not volunteer information about questioned results or practices until confronted with documentary evidence."



CONTRADICTORY PHYSICS. The data shows the temperature-dependent resistance reported in a paper[3] on superconductivity in carbon-60. This curve was extracted and enlarged from a figure showing 20 similar curves for different gate voltages. The investigative committee noted that one would not expect such a sharp transition from a virtually two-dimensional conducting layer. Furthermore, they found, the upper part of the curve came from an analytic expression, not real data. (Reproduced from ref. 1.)

In a letter submitted in response to the committee's report, Schön wrote, "I disagree with several of the findings and conclusions in the report of the investigation committee" but "I admit I made various mistakes in my scientific work, which I deeply regret." He added, "I never wanted to mislead anybody or to misuse anybody's trust." Schön still maintains that he "observed experimentally the various physical effects reported in these publications."

The responsibility of coauthors

The committee found Schön's coauthors to be "completely cleared of scientific misconduct." Schön had fabricated or falsified data "intentionally or recklessly and without the knowledge of any of his coauthors." Committee members were nevertheless troubled by the sticky question of determining the appropriate responsibility of coauthors. "We were in uncharted waters," Beasley said. As the report states, committee members could find "no widely accepted standards of behavior" and called on the community to establish some. For their investigation, committee members judged a coauthor's responsibility based on that person's "expertise, seniority, and level of participation."

The committee focused on the role of the senior coauthor, Bertram Batlogg (now at ETH Zürich). On one hand, they said he "took appropriate action once explicit concerns had been brought to his attention." On the other hand, they wondered whether he should have insisted on an exceptional degree of validation, given the wide attention he must have known such extraordinary results would receive. Batlogg has earned a distinguished reputation in the community, but a number of observers, such as Arthur Hebard of the University of Florida, Gainesville, now find it hard to understand why Batlogg never went to Konstanz to look over Schön's shoulder.

Batlogg acknowledges his responsibility as a coauthor to ensure the validity of the data. In an e-mail sent to reporters in October, Batlogg wrote that, at the time of the experiments, he had asked for additional data and experimental details. In retrospect, he realizes, those requests were not enough. Batlogg wrote, "As a result of this experience, I will apply additional and even more stringent checking procedures in the future. However, trust in colleagues shall and must remain one of the foundations on which we build future research endeavors." Of Schön, Batlogg comments, "I am deeply disappointed that a gifted colleague allowed himself to give in to data manipulation."

One of Schön's other coauthors, Christian Kloc, also expressed bewilderment and anguish. Kloc said he doesn't see Schön as the monster that the press makes him out to be, but as a soft-spoken scientist whom he had watched making measurements and putting in long hours at the lab. He says he probably trusted Schön too much, but he doesn't yet know how to deal with colleagues in the future. "I need to have a certain amount of trust," Kloc told us: He prepares very pure organic crystals to share with groups around the world, and he can't possibly watch when each one makes physical measurements.

Publications and patents

Beasley's committee made no judgment about the validity of the work underlying the papers; it would be impossible to do so, they state, in the absence of original data, devices, and witnesses. Bell Labs sent a letter to the eight journals that published papers compromised by scientific misconduct, stating that it would be up to the individual coauthors to retract the papers. Many journal editors plan, as a first step, to wait for the coauthors' responses. *Nature* has posted a notice on the electronic version of each affected paper, alerting the readers about the inquiry and providing a link to the committee's report.

Martin Blume, editor-in-chief for the American Physical Society (APS), told us that the *Physical Review* gets 6 to 12 accusations of misconduct each year, but the vast majority of those incidents involve plagiarism, questions of authorship, or misbehavior of referees. "Very seldom if ever do we get hints of fabrication of data . . . although we don't know what's not being caught." He wonders why anyone would risk getting caught by publishing fabricated data that alleges spectacular results unless, perhaps, the person was what he termed a "true believer" who had hopes of getting credit when someone else confirmed the results.

Should the referees have picked up on the evidence for scientific misconduct? "No," answers Donald Levy (University of Chicago), editor of the *Journal of Chemical Physics,* and chair of the American Institute of Physics's journal editors' panel. Says Levy, "Referees need to assume that the authors are operating in good faith. Once you admit the possibility of fraud, it becomes nearly impossible to evaluate the paper. It would be very damaging to the progress of science if every paper had to be screened for fraud." AIP's CEO, Marc Brodsky, adds that the main tasks of a referee are to ensure that a paper reports physically reasonable phenomena and includes enough detail for people to question the results.

As for the patents based on the findings in question, Bell Labs has retracted the six relevant US patent applications and the corresponding ones abroad.

Community reaction

Especially coming in the wake of a case of scientific misconduct at Lawrence Berkeley National Laboratory (LBNL) involving Victor Ninov (see PHYSICS TODAY, September 2002, page 15), the Schön affair has both saddened and shaken the physics community. Many physicists are turning introspective. Says Dan Ralph of Cornell University, "You lie awake at night and wonder if it could happen in your group." According to McEuen, "We could all reexamine how we conduct ourselves in a research group. We need to instill a sense of ethics and lab practices in our students."

Regarding how much physicists question their collaborators, most recognize that there's a fine balance between guarding against misconduct and impeding teamwork. "I think science is great the way we do it," says Los Alamos's Ramirez. "It would be wrong to suggest changes on the basis of two anomalous cases." Hebard notes that "scientists tend to believe their colleagues and therefore can be easily deceived . . . but that's why science moves so efficiently."

Are the Schön and Ninov cases anomalies, or are there contributing circumstances? Philip Anderson (Princeton University) points to the terribly competitive community in which physicists find themselves. "Careerism is very much on the rise, but nothing pushes in the other direction," he asserts.

Institutional responses

APS is reviewing its guidelines for professional conduct, which were formulated in 1991. Arthur Bienenstock of Stanford, who heads the ethics committee for APS's panel on public affairs, is leading that effort. Bienenstock says that his group will consider the responsibility of coauthors, institutional responsibilities, and the education of students. The panel plans to submit the guidelines to APS for adoption this month.

Some observers have questioned whether Bell Labs management exerted adequate oversight of the research. John Rowell, a former Bell Labs director, recalls that Bell Labs used to have a far more stringent internal review than the universities. "It looks as though some of the old processes were forgotten or abandoned," he says. Other former Bell researchers recall the ubiquitous lab notebook, in which data were dutifully recorded.

Bell Labs' Murray admits that the use of physical lab notebooks has declined in this computer age. In the wake of the Schön incident, she said, Bell Labs has instituted a policy for keeping computerized research records, which will require researchers to strike out changes in their computer files and to archive the files. Under revised policies, Bell Labs scientists must also post all manuscripts on an internal preprint server for internal technical comments. Furthermore, Bell Labs has issued updated guidelines on how to document inventions and has promulgated a research ethics statement.

Might something still be salvageable from the once promising research? Ramirez, credits the Bell Labs researchers with having made field-effect devices out of single organic crystals. Other experimenters during the past decade have been exploring the field effect in superconducting oxides, with solid, albeit less dramatic, results. According to Jochen Mannhart of the University of Augsburg in Germany, who has worked on such systems, the relevant parameter is not the breakdown field but the achievable polarization—and researchers are getting close to the polarizations claimed by Schön. Both Mannhart and Ramirez hope that at least some of the phenomena reported in the compromised papers will be found. Only time will tell.

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CERN Group Detects More than 100 Antihydrogens

> The mating of a positron to an antiproton is a significant milestone along an arduous path toward a comparison of matter with antimatter.

Does an atom of antihydrogen ($\bar{\mathrm{H}}$) have the same energy levels as its charge conjugate, the hydrogen atom? Yes, according to the venerable *CPT* theorem, which proclaims the invariance of the laws of physics under the simultaneous operation of charge conjugation (C), parity inversion (P), and time reversal (T). Does antimatter fall at the same rate as ordinary matter in a gravitational field? It should, if the equivalence principle of general relativity holds. Although *CPT* invariance has been tested to high precision in several systems, its importance impels us to explore its limits: Comparing H to $\bar{\mathrm{H}}$ should provide the most sensitive test yet of a system involving both a baryon and a lepton. As for gravitational properties, they have not yet been measured on antimatter. To conduct either test, though, one needs large quantities of $\bar{\mathrm{H}}$ atoms at low