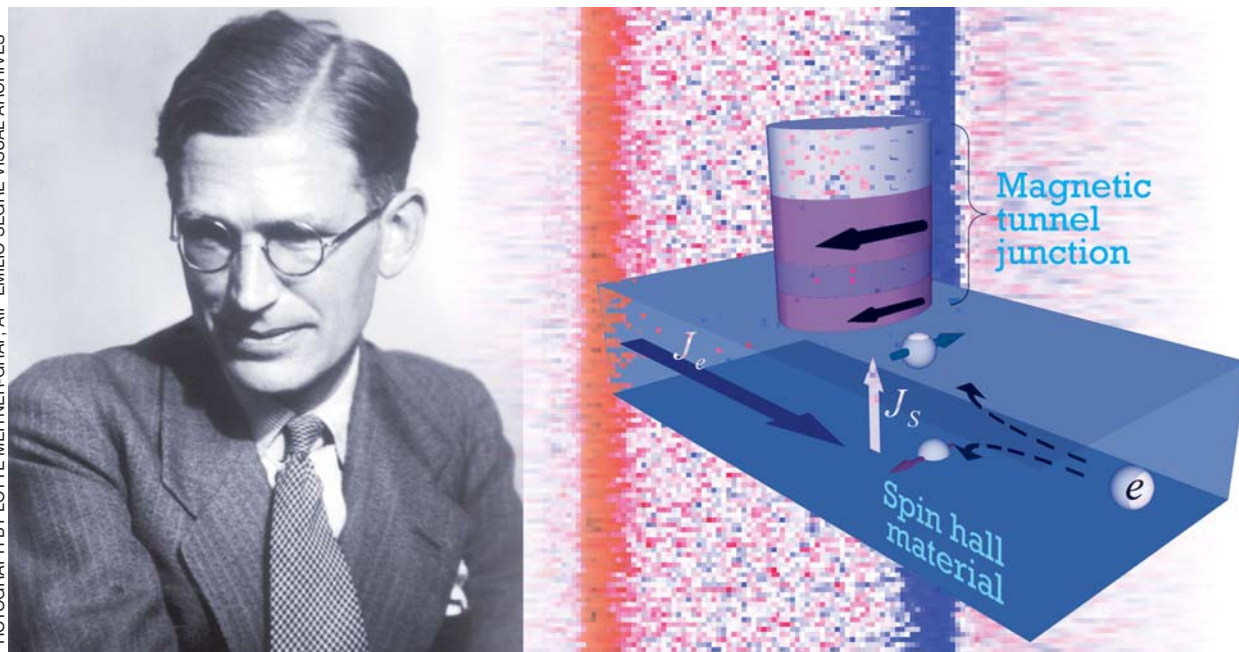


A reporter's look at the progress of **SCIENCE**

Charles Day

PHOTOGRAPH BY LOTTE MEITNER-GRAF. AIP EMILIO SEGRÉ VISUAL ARCHIVES



In 10 years, research can take many twists and turns—or not. Here's a sampling.

In 1929 the 23-year-old Nevill Mott asked himself whether the free electron has a magnetic moment that any conceivable experiment could detect. The question is subtle: Because of the uncertainty principle, an electron's intrinsic magnetic moment cannot be distinguished from the magnetic field that arises from its motion. But, as Mott argued, the electron's intrinsic magnetic moment can be quantified because the direction in which an electron scatters off an atomic nucleus depends on the orientation of the electron's spin.

Forty-two years after Mott's paper was published, Mikhail Dyakonov and Vladimir Perel of the Ioffe Institute in Leningrad identified a similar spin-dependent scattering effect in semiconductors, which, if verified, could be used to establish a transverse spin gradient. Known later as the spin Hall effect, the phenomenon was finally detected in 2004 (see *PHYSICS TODAY*, February 2005, page 17). Last year Cornell University's Robert Buhrman and his collaborators discovered a strong manifestation of the effect that operates in a brittle semimetal phase of tantalum.¹ The room-temperature effect, which is powerful enough to flip the spins in an adjacent ferromagnet, could serve as the basis of nonvolatile computer memory.

The image above shows Mott and the developments of 2004 and 2012. The 83-year path of spin-dependent scattering may be longer than we expect.

Still, it illustrates that science progresses and does so in steps whose size and separation are unpredictable.

To get a sense of how physics projects evolve on a decadal time scale, I recently conducted a modest investigation. Tracking down the researchers whose work I had written about in 2003 for *PHYSICS TODAY*'s Search and Discovery department, I asked them where their research had led. Their responses, which form the subject of this article, evince what you might expect, at least at a general level. Some projects begat new fields and new products; others changed direction or made only modest progress. But in their particular details, the responses were always surprising—and sometimes inspiring.

Science pays off

From a narrative point of view, one of the most interesting stories that I wrote in 2003 was about a paper by Dieter Braun,² who was a postdoc at Rockefeller University in New York City at the time, and his boss, Albert Libchaber (see *PHYSICS TODAY*, February 2003, page 16). The paper described a new method for boosting the local concentration of dissolved DNA in a small container using laser heating. The method was of potential importance because it could

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Figure 1. A section of rock sponge from the Lost City Hydrothermal Field located on the seafloor at 30° N near the Mid-Atlantic Ridge. The sponge's narrow fissures and its location near a heat source provide two ingredients—tight confinement and a thermal gradient—needed to concentrate prebiotic molecules. (Courtesy of Deborah Kelley, University of Washington.)

be used in the lab to handle large biomolecules. Moreover, the underlying phenomenon could conceivably have played a role in the origin of terrestrial life 3.5 billion years ago.

The most surprising element was not in the paper: Braun had discovered the method by chance. His original aim was to find new ways to measure the influence of temperature on biochemical reactants. Whereas using lasers to apply heat is commonplace, its combination with the method's other crucial element—tight confinement—came into play simply because scientifically interesting biomolecules are often available only in minute quantities.

Chance entered the story again when Braun sought an explanation for why a thermal gradient would prompt DNA and other molecules to concentrate within a small space. A colleague's passing remark led to the answer: thermophoresis, a convective phenomenon discovered in 1856 by Carl Ludwig and investigated further by Charles Soret two decades later. By optimizing the conditions, Braun found he could boost the local concentration

of dissolved DNA by a factor of 1000 compared with the unconcentrated average.

In the 10 years since the paper appeared, I had occasionally spotted papers by Braun and his collaborators, but I was stunned by his answer to my recent query about his progress. Braun, who now leads his own group at the Ludwig-Maximilians University of Munich, told me that the 2002 paper was the “trigger and foundation” of his whole career. In 2011 he was awarded the €100 000 (\$134 000) Klung-Wilhelmy-Weberbank Prize, bestowed on outstanding young German physicists or chemists.

He and his collaborators found that thermophoresis also works in a hot, natural setting: the thin fissures that thread through rocks found near undersea thermal vents (see figure 1). One of his group's most recent papers has established that thermophoresis not only concentrates RNA molecules, it also promotes their polymerization, an essential step in RNA-based scenarios for the origin of life.³

Five years ago Braun and two of his graduate students founded a company, NanoTemper Technologies, to market sensors that exploit thermophoresis to measure biomolecule binding. The Munich-based company now employs more than 15 people and has sold more than 80 sensors at €100 000 each. “Already, the taxes paid by that company are more than I ever spent in academia,” Braun told me. “Science really does pay off!”

Ultrashort

My story “Ultrashort laser pulses beget even shorter bursts in the extreme ultraviolet” appeared on page 27 of the magazine's April 2003 issue (see figure 2). The subject was a paper by a team led by Ferenc Krausz,⁴ who was then at the Vienna University of Technology. Having achieved the ability to control the phase of the electric field of few-femtosecond laser pulses, Krausz and his colleagues used the pulses to induce argon atoms to emit bursts of UV light that lasted a mere few hundred attoseconds (1 as = 10^{-18} s).

I already knew about some of Krausz's subsequent work, because we had covered it. In 2004 his team used 250-as pulses to trace the petahertz oscillations of an optical pulse's electric field (see PHYSICS TODAY, October 2004, page 21). Two years later he collaborated with Marc Vrakking of the FOM Institute for Atomic and Molecular Physics in Amsterdam on an experiment that controlled the light-induced breakup of a singly charged deuterium molecule D_2^+ . Thanks to their ability to control the phase of short laser pulses, Krausz and Vrakking could predetermine which of the two disassociated D atoms inherited the molecule's lone electron (see PHYSICS TODAY, June 2006, page 13).

Krausz's more recent work uses attosecond pulses as a probe. In 2010 he and his team discovered that when a 100-eV light pulse impinges on a neon atom, electrons from the atom's $2p$ orbitals take 21 ± 5 attoseconds longer to be kicked out than do electrons from the $2s$ orbital.⁵ Subtle electron-electron correlations are the delay's most likely cause.

That same year the researchers resolved the motion of valence electrons in krypton ions.⁶ More recently, Krausz and his collaborators demonstrated the ability to change the AC conductivity of a dielectric, silica, by 18 orders of magnitude within 1 femtosecond. The feat has implications for ultrahigh-frequency signal processing (see *PHYSICS TODAY*, February 2013, page 13).

Three-dimensional optical storage

I did my PhD thesis at Cambridge University's Institute of Astronomy in the mid 1980s. Back then, astronomical data were stored on magnetic tapes. Although the tapes' information density was orders of magnitude lower than that of today's optical and magnetic disks, wound-up tape, unlike the surface of a disk, exploits all three spatial dimensions.

In the summer of 2003 a paper came out that described a way to combine a tape reel's 3D storage with a disk drive's speedier access to stored information.⁷ The paper, by Yongchao Liang, Alexander Dvornikov, and Peter Rentzepis of the University of California, Irvine, was the subject of "Composite molecules store rewritable digital data" (*PHYSICS TODAY*, September 2003, page 21).

The concept behind the research was straightforward. Find a dye molecule whose ability to fluoresce is switched either on or off depending on the wavelength of the incident light. Embed the molecules in transparent plastic. The storage bits would correspond to voxels of the dye-embedded plastic. Access to individual voxels would be effected by aiming two perpendicular lasers at them. Where the beams converged, two-photon absorption at the sum frequency would ensure that only the intended bit would be read, written, or erased.

Rentzepis and his colleagues could not identify a single molecule that had all the right properties, so they grafted two different ones together: a molecule that can be optically switched between polar and nonpolar states and a dye molecule that fluoresces only in a nonpolar environment. Back in 2003 Rentzepis, Liang, and Dvornikov demonstrated that the concept worked. The prototype that they built reliably wrote, read, and erased data for 10 000 cycles. Where had that line of research reached after 10 years?

Rentzepis told me that he and his colleagues developed the technology to the point that they could store more than 10 terabytes in a plastic cylinder with a bit error rate that surpassed the data-storage industry standard. They also devised and developed a path toward boosting both capacity and switching rates. After being granted several patents, which were assigned to the University of California, Rentzepis concluded that the research had reached the point at which a company should pursue it. Call/Recall of San Diego took over the project and introduced its first 3D storage device in 2007. Rentzepis moved on to other things.

Cancer-fighting nanoparticles

In August 2003 the American Association for Cancer Research held its annual meeting in Washington, DC. Out of curiosity and because the meeting was

local, I spent a day there. One of the best talks I attended was by Gregory Lanza of Washington University in St. Louis.

Like others, Lanza and his Washington University collaborator Samuel Wickline were investigating the use of nanoparticles to diagnose and treat cancer. The approach is promising (see the article by Jennifer Grossman and Scott McNeil, *PHYSICS TODAY*, August 2012, page 38). Nanoparticles can be coated with anticancer drugs, with molecules that stick to cancer's molecular markers, and with contrast agents that enhance the visibility of even tiny tumors in x-ray or other types of medical image. And of course, nanoparticles can easily be introduced into a patient's bloodstream. In principle, a tumor could be destroyed without the doctor knowing at first where it is.

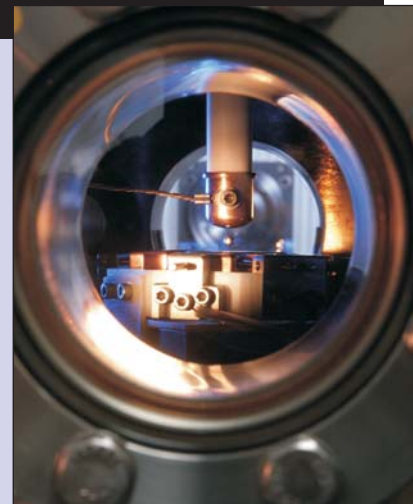
Lanza and Wickline's nanoparticles were coated with antibodies for integrin, a transmembrane protein. Integrins take part in angiogenesis, the process by which tumors assemble the blood vessels they need to gain access to nutrients. If angiogenesis is thwarted, tumors cannot grow. The nanoparticles were also coated with gadolinium ions that serve as a potent contrast agent in magnetic resonance imaging.

Electrostatic levitation

This photograph originally appeared on the cover of the July 2003 *PHYSICS TODAY* and accompanied a story (page 24) I wrote for that issue. At the center of the image sits a small metal bead held up by electrostatic fields and about to be melted by a laser. Before, during, and after the melting, the bead's crystalline structure will be probed by an intense beam of x rays. The experiment, conducted by Kenneth Kelton of Washington University in St. Louis and his collaborators, vindicated a 1952 theory that sought to explain why, unconfined and in the absence of impurities, liquid metals can be cooled tens to hundreds of degrees below their freezing points.

Kelton's paper about the 2003 experiment¹⁶ has been cited more than 200 times. Since then, he and his collaborators have extended the use of the levitation chamber beyond metals to semiconductors and beyond structure as a dependent variable to density and viscosity. Kelton and his collaborators have built and tested a new chamber that will make it possible to conduct neutron diffraction experiments on levitated samples at the Spallation Neutron Source at Oak Ridge National Laboratory in Tennessee.

The team's most recent levitation study looked at the glass-forming alloy $\text{Cu}_{100-x}\text{Zr}_x$ and explored the dependence on x and temperature of both the fragility and expansivity of the liquid. The results¹⁷ could pave the way for identifying optimal conditions for forming bulk metallic glasses. (For more about these materials, see the article by Jan Schroers, *PHYSICS TODAY*, February 2013, page 32.)



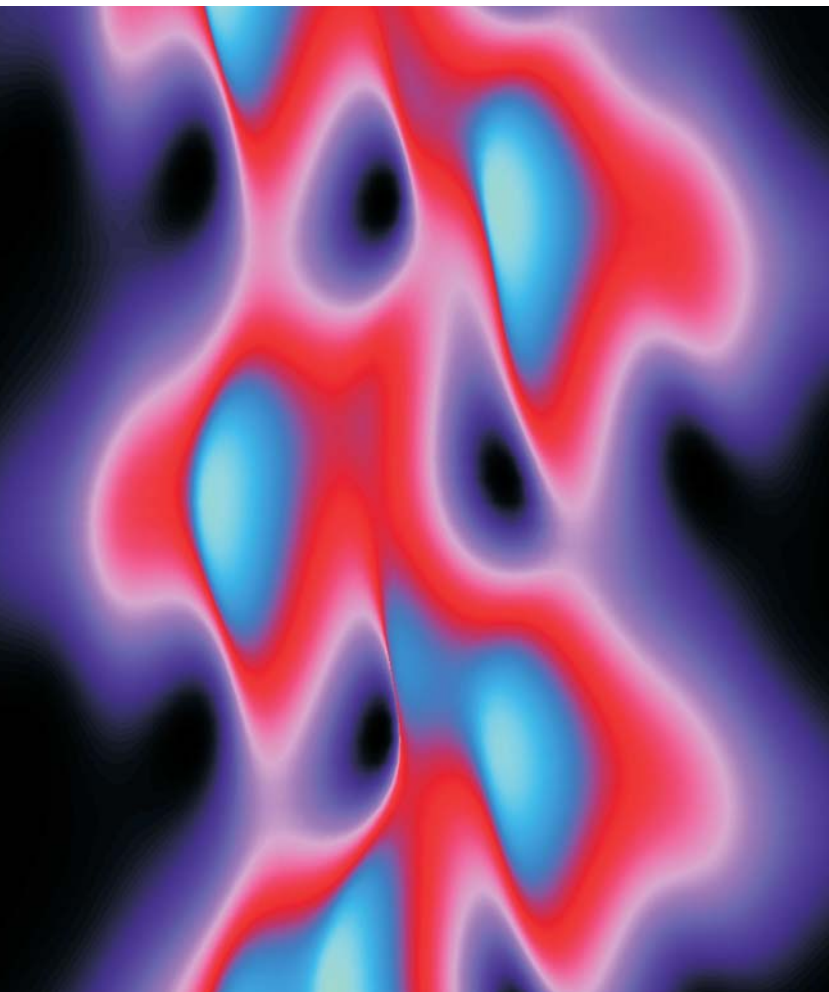


Figure 2. A streak image of a simulated ultrafast pump-probe experiment that explored how the kinetic energy (displayed in false color on the horizontal axis) of UV-induced Auger electrons changed with the delay (vertical axis) between attosecond pump pulses and femtosecond probe pulses. Color represents electron intensity. This image, which appeared on PHYSICS TODAY's April 2003 cover, and others like it embody temporal information about the attosecond decay of an atomic vacancy. (Courtesy of Ferenc Krausz, Max Planck Institute of Quantum Optics.)

Using those two coatings was not especially novel. What attracted me to the research was the nanoparticles themselves. Lanza and Wickline made their nanoparticles from an emulsion of an octane derivative and water.⁸ In my October 2003 story, "Nanoparticles locate and flag the blood vessels that nourish tumors" (page 26), I likened the production process to making salad dressing from olive oil and balsamic vinegar.

Lanza and Wickline are still pursuing emulsion-based nanoparticles, and they have made considerable progress. When I contacted Lanza in September, he told me that their nanoparticles are in early clinical trials both for imaging the sites of angiogenesis and for delivering an antiangiogenesis drug that they and their colleagues developed and licensed. Once the nanoparticles pass further health and safety tests, they will be submitted to the US Food and Drug Administration for evaluation as

what is known in the world of pharmaceutical regulation as an investigational new drug.

Extreme turbulence

The editorial offices of PHYSICS TODAY are close to the College Park campus of the University of Maryland. In January 2003 I took advantage of that proximity to visit Daniel Lathrop in one of his labs at the university. Besides the attraction of conducting an interview in person rather than over the phone, I wanted to see firsthand the turbulence experiment that I planned to write about for the March issue of that year.

The goal of the experiment was to study the small-scale 3D velocity gradients present in a turbulent liquid during powerful but rare changes in large-scale turbulent flow. Characterizing the statistical distribution of such events requires long, uninterrupted observing times. And because Lathrop and his graduate student Benjamin Zeff wanted to examine how vorticity interacts with dissipation, they had to resolve motion on the length scale over which dissipation occurs.

Their setup consisted of a cubic transparent box 22 cm on a side, filled with water and 3 trillion fluorescent micron-sized polystyrene beads. Two horizontal metal grids inside the box moved up and down to agitate the fluid; green laser light illuminated the beads; a high-speed video camera tracked their motion; sophisticated software harvested and analyzed the data. For the 10-Hz agitation that Lathrop and Zeff used, the dissipation scale was 0.75 mm and the Reynolds number was adequately high at 48 000.

Tracking of order 10^5 particles within a 1-mm³ volume proved too difficult because the camera could not determine a particle's distance with sufficient accuracy. Lathrop and Zeff chose instead to send into the box three thin, orthogonal sheets of laser light that intersected to define three sides of a cubic volume. Particles were tagged whenever they passed through one of the 1-mm² sides in a flash of green light. Using their high-tech implementation, the Maryland researchers could characterize flow events whose amplitudes lay up to 40 standard deviations above the mean.⁹

By the time I wrote about the experiment in March (page 18), Zeff had earned his PhD and left Lathrop's lab. Although they did not develop the 3D particle tracking technology further, Lathrop told me that his fellow fluid dynamicist, Charles Meneveau of the Johns Hopkins University in Baltimore, successfully adapted the so-called Lagrangian particle tracking approach for his theoretical and modeling work.¹⁰ However, Lathrop adapted the lessons that he and Zeff learned to image 3D structures in superfluid helium-4.

Indeed, when I contacted him in September, he had just received the page proofs of his latest paper, which reports the direct observation of Kelvin waves—long-wavelength perturbations that are excited when quantized vortices recombine.

Disappearing cooling flows

The biggest gravitationally bound structures in the universe are clusters of galaxies. Trapped within a

cluster's gravitational potential is a vast cloud of million-degree plasma whose x-ray emission is typically just as luminous as the combined optical emission of all the stars in all the cluster's constituent galaxies.

In 1978 NASA launched the *Einstein Observatory*, an x-ray telescope whose grazing-incidence optics provided the first clear images of what the cosmos looks like in x rays. When astronomers pointed the observatory at clusters of galaxies, they noticed that the x-ray spatial distributions of many clusters have strong central peaks. The peaks' emission is so intense that the concomitant loss of thermal energy implied that the internal pressure of the cooling plasma would be too weak to resist gravity's inward pull. The plasma—with a flux of up to 1000 solar masses a year in some cases—would slump toward the center of the cluster in what was dubbed a cooling flow.

Although the case for cooling flows was physically compelling, direct evidence of their existence was lacking for two decades. Then in 1999 the European Space Agency launched *XMM-Newton*, an x-ray observatory that is still aloft. Its grating spectrometer is capable of detecting and spatially resolving a sequence of iron emission lines whose individual peaks manifest different temperatures of the plasma. But in 2002, when John Peterson of Columbia University in New York City and his collaborators analyzed *XMM-Newton* data from 14 clusters, no iron lines from cool plasma showed up in the spectra. The plasma appeared to cool only to one-third of its starting temperature.¹¹ (See *PHYSICS TODAY*, March 2003, page 16.)

So then the pressing astrophysical question became not what happens to the plasma as it cools and converges, but what processes *prevent* the plasma from cooling and converging. The answer is still emerging. Most clusters that have large inferred cooling flows also have large central galaxies. Those galaxies have supermassive black holes. Because accretion of material onto black holes converts up to 10% of rest-mass energy into radiation, the energy emitted from a single black hole's immediate environs is sufficient to halt a cluster's cooling flow. Cooling flows have been subsumed into a newer, broader field that seeks to understand how black holes influence, and are influenced by, their surroundings.¹²

Disintegrating isomers

The most intellectually challenging news story I wrote in 2003 concerned an experiment that sought to determine how quickly acetylene, $\text{H}-\text{C}\equiv\text{C}-\text{H}$, isomerizes via a chemical reaction known as a 1,2 hydrogen shift to vinylidene, $\text{H}_2-\text{C}=\text{C}$ (see *PHYSICS TODAY*, August 2003, page 19). The experimental solution entailed combining three technologies: cold molecular beams, synchrotron light sources, and particle-physics detectors. Lew Cocke of Kansas State University and his graduate student Timur Osipov spearheaded the work.¹³

Although the two molecules are modest in size and the 1,2 hydrogen shift is among the simplest chemical reactions, the path by which the H atom

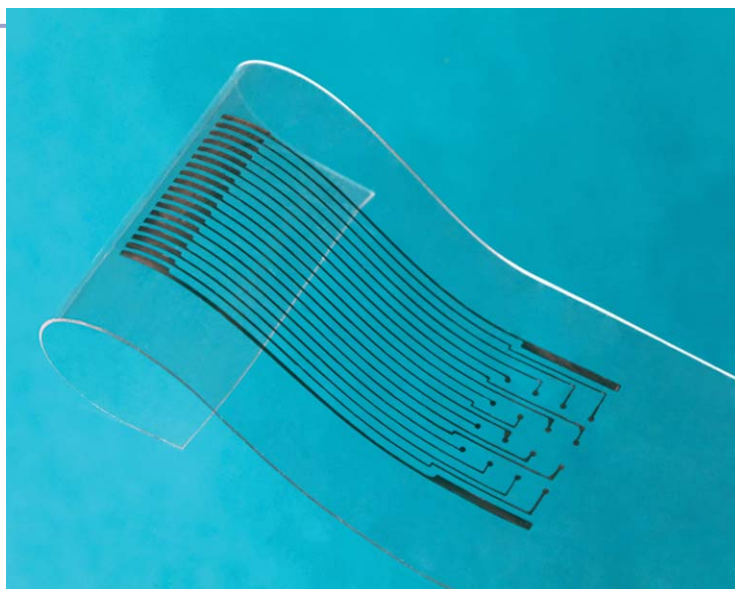


Figure 3. Implanted devices that monitor and treat the human nervous system must be biocompatible and flexible, as is the case for this prototype array of gold electrodes embedded in a sheet of soft silicone rubber. (Courtesy of Stéphanie Lacour, Swiss Federal Institute of Technology in Lausanne.)

hops from one C atom to the other cannot be calculated. To measure the reaction time, Cocke and Osipov zapped acetylene molecules with x rays to ionize them and induce isomerization, zapped them again to ionize them a second time and induce them to fragment, then measured the momenta of the fragments. Thanks to the experiment's ingenious design, Cocke, Osipov, and their collaborators could place an upper limit of 60 femtoseconds on the acetylene-to-vinylidene isomerization time.

When I asked about where the research had led, Cocke told me that in his view, the 2003 paper prompted the ultrafast community to investigate acetylene-to-vinylidene isomerization. Theoretical and experimental methods have been brought to bear on the pathway, which, besides serving as a model system, could shed light on how the 1,2 hydrogen shift plays out in biochemical reactions. Yuhai Jiang of the Max Planck Institute for Nuclear Physics and his coworkers recently used the FLASH free-electron laser in Hamburg, Germany, to perform a pump-probe investigation.¹⁴ They derived an isomerization time of 52 ± 15 fs.

"Frankly, in spite of a decade of further work," Cocke told me, "I do not think any of these experiments has produced a completely crisp picture of exactly what is going on."

Flexible conductors

Amy Ross designs space suits for NASA. Asked by *Parade* magazine to comment on the verisimilitude of the suits in this fall's hit movie *Gravity*, she characterized the data readouts that were projected onto the astronauts' helmets as science fiction. "We'd like to get there," she said, "but those technologies aren't real friendly with curved surfaces."

For *PHYSICS TODAY*'s July 2003 issue (page 26), I wrote about research that aimed to make flexible electronic devices for just such applications. Sigurd

How papers are chosen for coverage

In 2012 just one physics journal, *Physical Review Letters*, published 3995 papers, which turns out to be almost exactly 100 times the number of stories that ran in PHYSICS TODAY's Search and Discovery department in the same year. Identifying newsworthy papers in *PRL* and a host of other scientific journals is one of the most important and challenging tasks that the department's reporters face.

Some Search stories originate from unsolicited tips from physicists. More typically, the first step involves a Search reporter spotting a paper of potential interest in an advance table of contents, scanning a press release, or learning about the work through regular conversations with researchers or some other early-warning channel. To qualify as promising, the work must appear to constitute a significant step forward in its field and be judged to be of broad interest.

Once the paper has cleared that first hurdle, the Search reporter sends it to three or more experts who assess whether it does indeed merit coverage. The final step in the process takes place when the reporters hold their monthly meeting. Expert-endorsed papers are discussed and the Search team decides which stories will appear in the following issue. Although significance and broad interest are the principal criteria, the Search team also values variety of topic, both within a single issue and over the course of months and years.

Wagner of Princeton University and his postdoc Stéphanie Lacour figured out a way of depositing thin conducting stripes of gold on a flexible plastic that preserved the gold's conduction even when the substrate was subjected to strains of up to 40%.¹⁵

The result was potentially significant. Sensors and other components could already be made small enough to withstand their substrate's stretching, like the sequins on an ice skater's costume or the scales on a snake's skin. But the conducting interconnects have to be made of metal because the organic conductors, while flexible, lack the requisite conductivity. Before Lacour and Wagner's advance, metals deposited on a flexible substrate would break at strains of a few percent.

Lacour and Wagner applied for a US patent, which took six years to obtain. According to Wagner, the delay was caused by the patent examiner misunderstanding the distinction between flexible and stretchable. Only when he and Lacour visited the patent office in Alexandria, Virginia, and demonstrated their interconnects in person did the examiner understand what they had made. "Our patent was granted in short order," Wagner told me. (An extension of their approach, and organic-conductor developments, were described in PHYSICS TODAY, October 2008, page 18.)

Wagner continues to work on flexible electronics, as does Lacour, who runs her own group at the Swiss Federal Institute of Technology in Lausanne. Figure 3 shows one of her projects, a 14-mm array of gold electrodes deposited on soft silicone rubber. The array, or one like it, is designed to be part of a prosthetic device that electromechanically couples neural tissue to sensing electrodes. Flexibility is essential for such devices. Not only is the target organ, the spinal cord, highly curved, but the strains incurred during surgical implantation are also likely to be high.

Is it any wonder?

Over the past 15 years or so, PHYSICS TODAY has published about 40 Search and Discovery stories per year. Given the screening by our reporters (see the box at left), it is not surprising that research covered in the department has often turned out to be fruitful.

Still, my modest investigation has revealed aspects of scientific research that are worth repeating and reinforcing, especially to the politicians who control research funding. First, the time scale over which basic research bears fruit is unpredictable and sometimes long. The funding of short-term, targeted research at the expense of basic research could well curtail the development of unforeseen and promising applications. Second, universities play an important role in developing new and favorable lines of research. Spending 10 or more years on a project that expands our knowledge of the natural world without necessarily yielding a new product is far riskier for an industrial lab than it is for a university lab.

Lastly, the progress made in just 10 years by the groups in my investigation reminds me that science and its cousin technology are the fields of human endeavor that have advanced the most. Though you may disagree, despite the passage of centuries, no English writer has significantly surpassed William Shakespeare (1564–1616) in skill. Even today, some musicians proclaim Johann Sebastian Bach (1685–1750) as the greatest composer of all time. And in the 1780s, when James Madison and his fellow founders were writing the first US Constitution, Antoine Lavoisier was writing the world's first chemistry textbook. Whereas the current US Constitution is clearly superior to the unamended original, the leap from Lavoisier's textbook, which listed just seven known elements, to today's chemical knowledge is far, far greater.

In a given year, a PHYSICS TODAY reporter consults a large number of researchers for advice and help in understanding what is almost always unfamiliar research. If you're among the past and present ranks of advisers and interviewees, on behalf of my colleagues, "Thank you!"

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