The Trajectory of Techniques: Lessons From the Past

In 1908, the year he was awarded the Nobel Prize, British physicist Ernest Rutherford was at the University of Manchester studying alpha particles (charged particles emitted radioactively by certain nuclei), a cause to which he devoted much of his career. He was trying to measure their charge by shooting them into a small ionization chamber, only to find himself stymied by their maddening habit of ricocheting every which way off air molecules blocking their paths. The result: inconsistent and unreliable measurements. Occasionally, he found, they even backscattered a full 180 degrees off materials. Rutherford, a large, confident man with a booming voice who frequently spiced his conversation with off-color remarks, grew progressively annoyed: "The scattering is the devil," he complained to a friend that summer.

But Rutherford soon managed to turn the nuisance into a godsend. He knew that he had no choice but to understand and quantify the effect, which he had first noticed 2 years previously, if he wanted to improve the accuracy of his measurements of the particles' charge and mass. In the process, he realized that the way alpha particles scattered depended on the charge and mass distribution of what scattered them. And that, in turn, meant that alpha particle scattering could be used as a structural probe. By observing the distribution of alpha particles after scattering—which he did thanks to the tiny flashes they produced upon striking a scintillation screen—one could glean information about the internal structure of the scattering medium. Suddenly, scattering was not an annoyance but rather a potentially invaluable research technique.

Three years later, in 1911, Rutherford and his assistants had used scattering to discover the atomic nucleus, high up on anyone's list of the momentous discoveries of the 20th century. And as if that weren't enough, alpha scattering next led, unexpectedly, to something equally momentous, the discovery of nuclear transmutation—that an alpha particle striking a nucleus could disintegrate it, transforming it into the nucleus of another element.

Indeed, scattering was to become a fundamental technique whereby high-energy physicists examine charge and mass distribution in microphenomena. And it's still in use: The 1990 Nobel Prize was awarded for an experiment in which energetic electrons were scattered off protons to obtain information about the quarks inside the latter. On a more mundane level, "Rutherford backscattering," using small energy accelerators and other commercially available technologies, has become one among a class of standard laboratory techniques to study impurities and near-surface phenomena in solids. The principle remains the same: examine how particles bounce off a surface and you get a picture of its microscale structure.

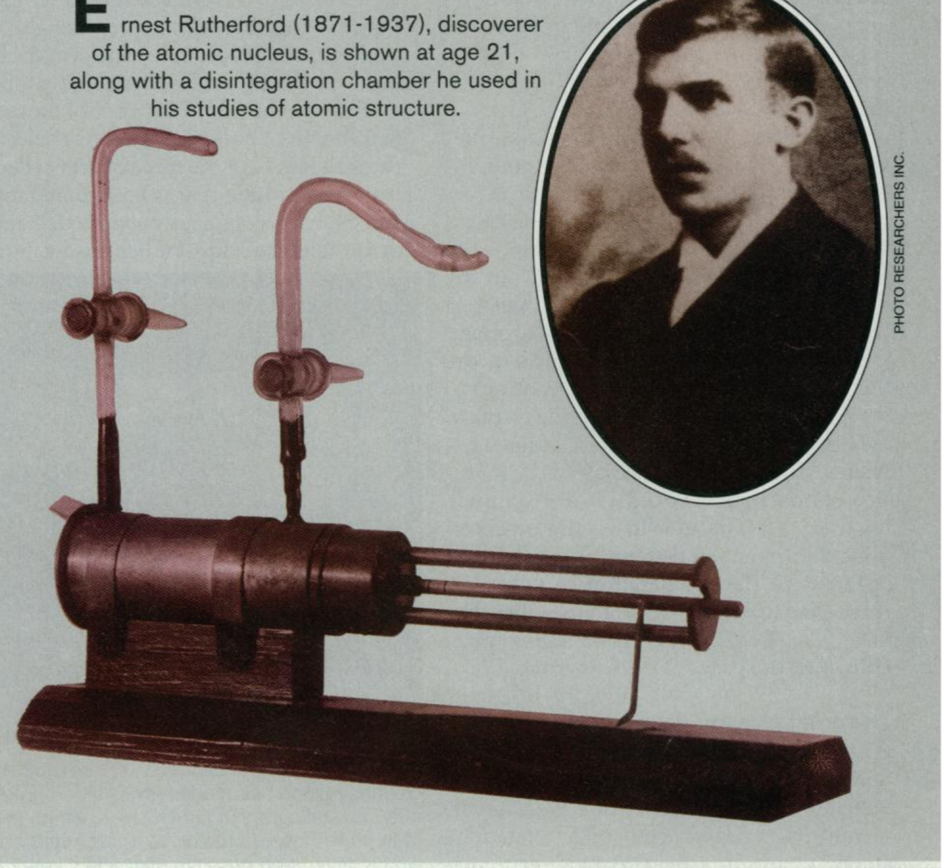
Effects, techniques, technologies

Techniques play a key role in everything from Nobel-class discoveries to routine measurements carried out by technicians. Although technique is a word that has meaning in a wide variety of contexts, in science it generally refers to a practice that can be repeated to produce measurements or prepare objects for measurement or manipulation. A technique, one might say, is a "knowledge-producing tool." Given the omnipresence and diversity of techniques, it might seem difficult to say much of value about their general nature. Nevertheless, several rules of thumb can be extracted from consideration of a few historical examples—rules of thumb that researchers rarely reflect on explicitly in directing their attention to inventing, using, and improving techniques. These rules touch on how effects evolve into techniques and then into technologies, how the level of skill required for their use declines over time, and how they continue in use over long periods, being modified until they would be almost unrecognizable to their inventors.

Take the classic trajectory—well illustrated by Rutherford's discovery and exploitation of scattering—that is frequently followed by scientific phenomena as they pass from newly discovered effect to laboratory technique and finally to technology. An effect is a characteristic, instructive, or useful consequence of a scientific phenomenon; examples include the Mossbauer effect (the recoiless absorption and emission of gamma rays by nuclei in a crystal) and the Josephson effect (the tunneling of an electron across a barrier between superconducting materials). When an effect is sensitive to some sought-after parameter of a system (as Rutherford's alpha scattering was to charge and mass distribution), it can be turned into a technique, because the effect can be used to alter, analyze, or measure that parameter. And it is

Scatter Brain

Ernest Rutherford (1871-1937), discoverer of the atomic nucleus, is shown at age 21, along with a disintegration chamber he used in his studies of atomic structure.



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always possible that the technique can mutate further—into a technology. This happens when it becomes sufficiently standardized that it can be performed by commercially available "black box" instrumentation, whose principles do not have to be fully grasped by its user.

From heroism to routine

The story of scattering also illustrates the crucial role of skill; one must not only pick the right effect but also be able to exploit it lest results be inconsistent. This is nicely illustrated by another story: how a test for syphilis was developed by the German bacteriologist August von Wassermann, which was the subject of an influential monograph in the philosophy of science published in 1935, *Genesis and Development of a Scientific Fact*, by bacteriologist and science methodologist Ludwik Fleck. In 1906, the year Rutherford first noticed scattering, von Wassermann was director of the division of experimental therapy and serum research at the Robert Koch Institute for Infectious Diseases in Berlin, where he was seeking evidence for the presence of causal agents of the disease in organs and blood. But von Wassermann's assumptions proved faulty, and he and his co-workers wound up being more successful at detecting the presence of what he thought were syphilitic antibodies, through an effect later called the Wassermann reaction. The reaction brings about the appearance or nonappearance of hemolysis (destruction of red blood cells), a process visible to the naked eye, which indicated, so von Wassermann thought, the presence or absence of syphilitic antibodies.

In this case, the technique-begetting effect, while unexpected, was not a nuisance. Von Wassermann realized that if the effect could be made reliable and consistent, it could be turned into a test for detecting syphilis, which would be of enormous medical significance. Von Wassermann and his co-workers made a midcourse correction in their research program and turned their attention to developing such a technique. But since their understanding of the reaction was crude, they had to rely initially on their "serological touch"—their intuitive skills in the laboratory—to get successful results.

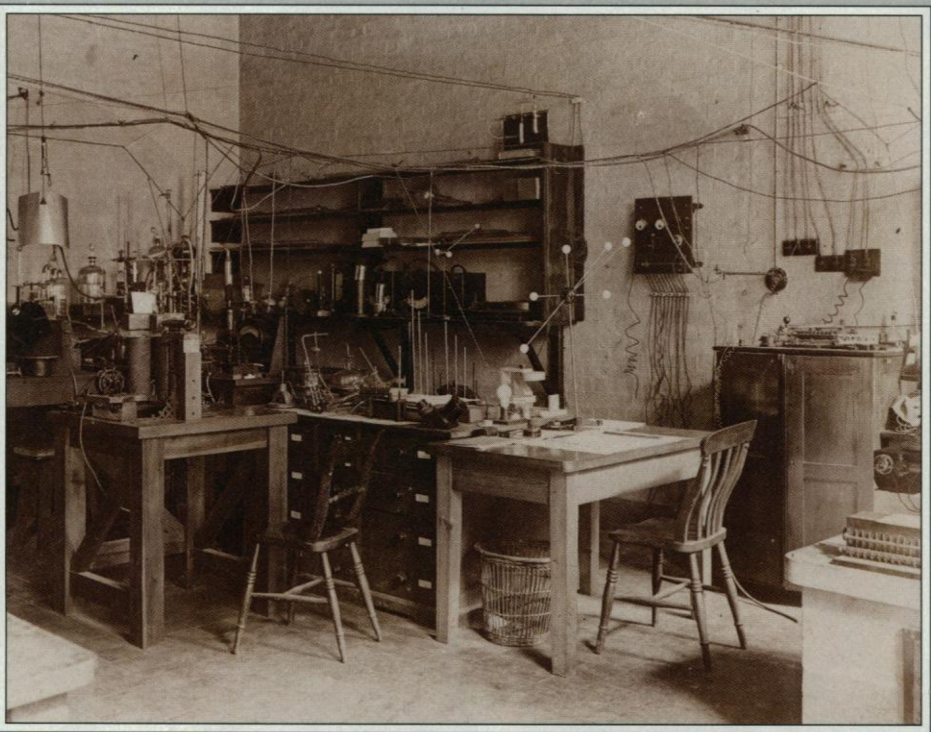
"The scattering is the devil," complained Ernest Rutherford. But before long the "devil" had opened the door to discovery of the atomic nucleus.

In their first experiments, for instance, the technique turned in positive results a mere 15% to 20% of the time, and only later did the success rate climb to 70% to 90%. Initially only von Wassermann and his co-workers could get the technique to work; the addition of new members to the research team would disrupt results for a time. Moreover, other scientists who wished to learn it had to come to Berlin to work in Wassermann's laboratory. And when the League of Nations sponsored a series of "Wassermann Congresses" at which top serologists worldwide examined the same blood samples independently, the results varied by a small—but significant—amount. Eventually, improvements were incorporated that desensitized the reaction, making its course less dependent on particular lab environments and on the skills of particular individuals. Today, the test is standardized and relatively routine and is one of a number of techniques for diagnosing syphilis.

The story of the Wassermann reaction shows neatly that the discovery and early use of an effect is often "heroic," requiring the ingenuity of brilliant scientists like Rutherford or von Wassermann as well as state-of-the-art instrumentation—ordinary levels of skill are simply not enough. But for an effect such as scattering or the Wassermann reaction to be turned into a technique, the need for heroism must then be dramatically reduced, so that the technique can be put to use repeatedly and reliably, not just by one ingenious person but by others who are merely skilled at the level of ordinary mortals. Who would want a syphilis test that didn't yield accurate results unless the doctor performing it was a genius?

Techniques beget techniques

As an effect becomes a technique, the level of skill required to put the effect to practical use is not the only element that changes. In addition, the technique proliferates, assuming new guises and new purposes, as the following story of accelerator physicist John Blewett shows. In 1946 Blewett, working at a General Electric (G.E.) plant in Schenectady, was handed an issue of *Physical Review* by his section director, who suggested he look at a three-paragraph letter by Russians D. Iwanenko and I. Pomeranchuk concerning energy loss in accelerators. The authors pointed to an overlooked consequence of the laws of classical electrodynamics. Those laws held that charged particles moving in a magnetic field radiate energy, and the Russians noted that the effect rose sharply with the size of particle accelerators. That effect imposed "a limitation for the maximal energy attainable" by such devices, they said. Blewett



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Rutherford's working space at the Cavendish Laboratory at the University of Cambridge. Rutherford moved to Cambridge from the University of Manchester, where, in 1908, he had turned alpha scattering–initially an experimental annoyance–into a key tool for analyzing the microscale structure of the atom.

was building large circular electron accelerators for G.E. as x-ray sources; dismayed, he set out to see whether the bad news was true.

It was. Electrons in large particle accelerators would radiate energy tangentially to their orbits, like a spinning wheel throwing off mud. Blewett was able to detect the effect in a 100 MeV "betatron" that was already operating at G.E. Indeed, engineers there had noticed an unexpected shrinkage in the orbit of the rotating particles, but they had attributed the shrinkage to defects in the magnet. When they heard Blewett's disturbing news, they understood what was happening: The orbits were shrinking as the particles lost energy, radiating it away into space just as the Russians had predicted.

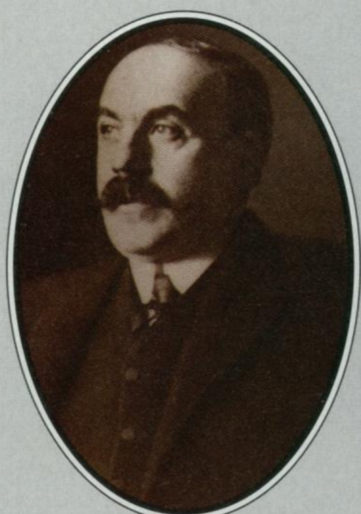
For a time, some researchers called the effect "Blewett radiation," but it was soon universally dubbed "synchrotron radiation." In 1947 G.E. scientists actually observed firsthand the troublesome effect, in a long-planned 70 MeV synchrotron. The machine had a transparent vacuum chamber with a mirror installed in such a way that the inside of the chamber could be seen while the device was in operation. With that setup, scientists were able to observe a small, bluish-white speck of light that represented the visible portion of the radiated energy. Synchrotron radiation was one of the few new effects in physics that were visible to the naked eye, and the observation caused a small stir among G.E. bigwigs. But among accelerator physicists, the novelty of the phenomenon's visibility was small consolation for the dismal prospect of a point of diminishing returns for accelerators; at some scale, extra energy added to the electrons would be promptly radiated away. "I was considerably annoyed," says Blewett, "and that was the general reaction of the whole community."

But Blewett's annoyance didn't last—and ultimately he spent a good deal of time working on ways to develop the erstwhile nuisance. In 1953 two Cornell scientists, P.L. Hartman and D.H. Tomboulian, constructed a primitive beam line to carry off the synchrotron radiation and measure properties such as at what angles and energies it was thrown off. In 1960 two National Bureau of Standards scientists, Robert P. Madden and Keith Codling, first showed that synchrotron radiation had new physics applications when they used it to study the excitation spectrum in gases. By the mid-1960s, enough new physics applications had been uncovered so that when funding dried up for a proposed electron-positron accelerator at the University of Wisconsin, scientists converted the prototype into a device to produce synchrotron radiation; when funding nearly fell through a second time, the seemingly ephemeral machine was baptized "Tantalus." The first machine specifically dedicated to producing synchrotron radiation and harnessing it as a technique, Tantalus came on line in 1968. Meanwhile, this technique for producing monochromatic light was incorporated into many other techniques relying on x-rays or ultraviolet radiation, and synchrotron radiation sources were soon used in x-ray crystallography, x-ray microscopy, x-ray lithography, venous cardiac angiography, spinpolarized photoemission spectroscopy, UV circular dichroism, and others.

In the mid-1970s, a second generation of synchrotron radiation sources arose. Blewett himself was the coauthor of the proposal for one of the first machines, the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. Thirty years after he was "considerably annoyed" to uncover an effect that appeared to curtail dreams for ever larger accelerators, and a decade and a half after the effect was used as a technique for producing monochromatic light, Blewett found himself working on a device to produce synchrotron radiation deliberately in the service of a wide variety of techniques.

The Healing Serological "Touch"

German bacteriologist August von Wassermann (1866-1925), was the developer of the first reliable test for syphilis. In 1906, von Wassermann was director of the division of experimental therapy and serum research at the Robert Koch Institute for Infectious Diseases in Berlin. Early in their work, von Wassermann and his colleagues found that the key indicator was an effect–later known as the Wassermann reaction–that results in hemolysis, the destruction of red blood cells. Initially, however, the researchers had to rely on their highly refined lab skills, or serological "touch," to get successful results; people from other labs couldn't reproduce the results.



THE BETTMANN ARCHIVE

Before long the test had become routinized and no longer depended on the skill of von Wassermann and his associates. Soon large campaigns to eradicate syphilis were being carried out. In the photo at right Mrs. Wright Macmillan, chairman of the hygiene committee of the League of Women Voters, sets an example by taking the Wassermann test in 1937.

UPI/BETTMANN

Techniques absorb other techniques

Techniques don't always develop just in relation to effects; they also grow and absorb other techniques into themselves. This is illustrated by the example of a technique developed by H.G.J. ("Harry") Moseley, who joined Rutherford in Manchester around the time he began the scattering experiments that resulted in the discovery of the nucleus. Moseley was brilliant, determined, and serious to a fault: He often worked at the lab straight through the night, to Rutherford's consternation, and was the only person who openly disapproved of the latter's frequently spicy language. Moseley became interested in x-rays and noted that in principle the nuclear charge of different elements could be inferred by measuring the frequency of the x-rays produced when an electron drops into the K, or inner-most, electron shell; the frequency of the x-rays would depend on the nuclear charge of the element. Measuring nuclear charge bore on the issue of whether the elements should be ranked in the Periodic Table by order of their atomic weight or by some other quantity, an absolutely fundamental but as yet unsettled question.

In 1913 Moseley settled the issue using a technique still celebrated for its cleverness and simplicity. Inside a 1-meter cathode ray tube, he installed a miniature track on which he placed a set of tiny aluminum trolleys bearing samples of different elements. He could cause the trucks to move in and out of the cathode ray (electron) beam via silk fishing lines wound on brass bobbins, so that each sample could be exposed in turn. Under the cathode-ray bombardment, some K shell electrons of the sample would be knocked out and other electrons would fall in to replace them, producing x-rays, which could be recorded on a photographic plate.

Harry Moseley died a patriot's death at Gallipoli before reaching the age of 28, but by then he had perfected a simple, brilliant method of analyzing nuclear structure.

With this elegant technique, Moseley determined for the first time that nuclear charges of the different elements were integer multiples of the charge on a hydrogen nucleus, that "these integers are really characteristic of the elements," and that they were the salient numbers to use in building up the Periodic Table. Moseley quickly exploited his technique to rank the order of the rare earth elements, to analyze the composition of samples, and to expose as false the discovery of the nouveau element "celtium," announced 2 years previously. The technique, in a few days, settled a score of issues that chemists had struggled over for years and in some instances decades.

But Moseley did not live to see it developed further; in 1914 patriotism motivated him, over Rutherford's objections, to volunteer for the war effort, and he died senselessly at Gallipoli in 1915, not quite 28 years old. Fortunately, use of the technique did not die with the young Englishman. Later, Moseley's method was progressively refined by others, and its use contributed to a greater understanding of atomic structure; that knowledge, in turn, brought about improvements in the use of the technique, which resulted in even more structural discoveries. Moreover, other techniques were absorbed into Moseley's original method, transforming it into something rather different. Beams of finely tuneable and tightly focused photons from synchrotron radiation sources, for instance, were used to knock out the inner electrons. These were preferable to beams of charged particles because they deposited less energy in the sample.

As a result of these improvements, the technique keeps reappearing in new incarnations, which Moseley himself would hardly recognize as being related to his. In 1992, first prize in the Westinghouse Science Talent Search contest went to 16-year-old Kurt Thorn for a study of shellfish pollution in Long Island Sound. Thorn used a technique for detecting pollutants, sensitive to one part per million, that is a direct descendant of Moseley's. X-rays from a beam at the NSLS were focused down to a diameter of 8 microns and directed against samples of clamshells. A detector picked up x-rays created by electrons falling into the K or L shells to replace electrons knocked out by the beam. "What I did," Thorn says, "had been tried before with other techniques, but the results weren't good because either the intensity or position resolution was poor. My technique was neat, because it provided high intensity and great spatial resolution, so that you could detect trace elements and pinpoint their exact location on the growth rings of the shells."

Thorn's technique, although identical in principle to Moseley's, seems very different. X-rays replace cathode rays; removable glass slides replace miniature trolleys; a lithium-drifted silicon detector replaces the photographic plate. Thorn even knew the technique by a different name than Moseley knew it by: x-ray fluorescence microprobing. The incorporation of other techniques greatly increased the range of the original method. But at the same time, the technique entered the anonymous scientific toolbox, divorced from its creator—even from any knowledge of its creator. "Who's Harry Moseley?" asked Thorn.

The list of rules of thumb given in this article is incomplete. What is more, hordes of exceptions could be given to any of them. Others might come up with better lists of their own. Such an exercise would be useful for lab managers or investigators, because by carrying it out they would become increasingly alert to the factors that help in the development of useful techniques. Several useful hints, for example, emerge from this list, such as: Value nuisances! Find out whether what seemed like an interference can be turned into a useful probe of what is doing the interfering. Be patient with techniques that depend—at least temporarily—on a particular scientist's instinctive feel for the equipment, techniques that may not travel well outside the inventor's lab. Look for cases where one technology can improve another. If these cues are followed up, they could lead to a better understanding of the process by which techniques develop and mature—something that may prove increasingly important at a time when scientists are called on to be ever more productive.

–Robert P. Crease

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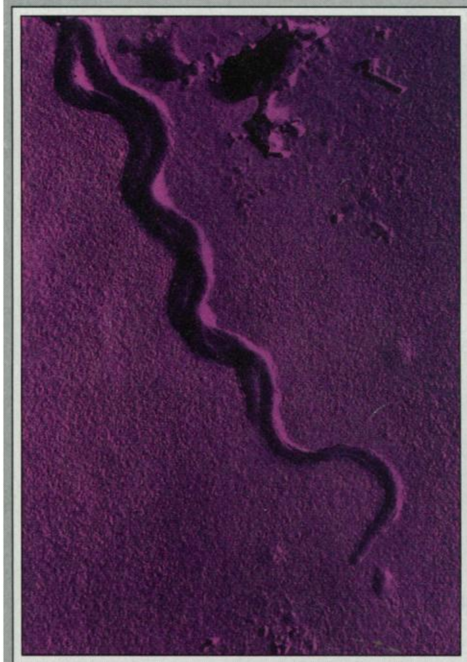

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The syphilis agent, *Treponema pallidum*, is a motile, spiral bacterium 6-15 micrometers long. Although von Wassermann's test was a great advance over all previous diagnostic measures, it was still not truly specific; the first truly specific test for *T. pallidum* was not developed until the late 1940s.