What was it about the magnetism of an iron bar that could divert Einstein from perfecting his celebrated theory of general relativity? **By Peter Galison**


PERCHING ON A LAZY SUSAN (or a giant compass needle) with a gyroscope in each hand: this is the kind of thought experiment that led Einstein and W. J. de Haas to successfully explain magnetism in iron. When counterclockwise-spinning gyros are held with their axes pointing outward, their opposing angular momenta add to zero (*center*). When the holder raises the gyros upward, their angular momenta align, so they sum to a nonzero value. Because the system's total angular momentum is conserved, the lazy Susan begins to rotate to compensate. Likewise (according to the Einstein-de Haas theory, which was later revised), when the orbits of electrons around iron atoms in a magnet are aligned by an applied magnetic field, the entire magnet begins to spin.

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# *EINSTEIN'S* COMPASS

**At the beginning of 1915, Albert Einstein found himself engaging more and more** in politics; he started to protest the militarism that had plunged Europe into a devastating war. That year also marked a significant change in the path of his long life in science. Collaborating with mathematician Marcel Grossman, Einstein was scrambling to learn all he could about a new kind of geometry, heretofore almost entirely unknown to physicists, that might aid him in characterizing the bending of spacetime. The stakes, he realized, were vast: Could special relativity be generalized into a theory of gravity? Could the Newtonian cosmos of distant inverse-square forces be scrapped in favor of one based on the equivalence of mass and energy with fields of curved space and time? In November 1915, after the most intense intellectual struggle of his life, Einstein was finally able to reveal general relativity to the world. His gargantuan effort was no less than a triumph of theory, reason and abstraction.

Yet from the start and through much of that eventful year, Einstein had stepped back from the Platonic reaches of tensors and coordinate transformations to focus on bench experiments involving gluing quartz fibers to mirrors and pulsing electric currents through electromagnets. As he wrote to his best friend, Michele Besso, on February 12: "The experiment will soon be finished.… A wonderful experiment, too bad you can't see it. And how devious nature is, if one wants to approach it experimentally! I've gotten a longing for experiment in my old age." Working with Hendrik Lorentz's son-in-law, W. J. de Haas, Einstein undertook an experimental challenge that had stumped some of the most adept lab hands of all time—explaining the mechanism responsible for magnetism in iron.

The basic concept was simple. An electric current traveling in a loop makes an electromagnet. Einstein wondered whether magnetized iron might not also owe its capacity for magnetization to a similar phenomenon, as André Marie Ampère and his successors had long speculated. Einstein asked whether, at the atomic or molecular level, there were many such current loops all oriented in the same direction. If so, there might be just one kind of magnetism. Said he:

> Since [Hans Christian] Oersted discovered that magnetic effects are produced not only by permanent magnets but also by electrical currents, there may have been two seemingly independent mechanisms for the generation of the magnetic field. This state of affairs itself brought the need to fuse together two essentially different field-producing causes into a single one—to search for a single cause of the production of the magnetic field. In this way, shortly after Oersted's discovery, Ampère was led to his famous hypothesis of molecular currents which established magnetic phenomena as arising from charged molecular currents. [from "Experimenteller Nachweis der Ampèreschen Molekularströme," by Einstein and de Haas, in *Deutsche Physikalische Gesellschaft,* Vol. 17, page 152; 1915]

Reducing two causations to one: here was quintessential Einstein. He had begun his work on special relativity with the assertion that the usual understanding of James Clerk Maxwell's equations must be very wrong, because it seemed as if there were two explanations for why current was produced when a wire coil approached a magnet. If the coil was moving and the magnet still, the standard story held that this was because the charge in the coil was moving (along with


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GYROSCOPIC DIRECTION FINDER, perfectly suspended so that it can rotate in any direction, will continue to point toward the same location in the heavens even as the earth spins and orbits. At any latitude away from the North Pole, however, as the earth turns, the gyro will leave the plane parallel to the ground—making it awkward to use for navigation.

the wire) and so was pulled around the loop by the magnetic field. If the magnet was moving toward the coil, then, according to the conventional view, the growing magnetic field near the coil was produced by an electric field that drove charge around the coil. Einstein's special theory of relativity accounted for both phenomena by reassessing the meaning of space, time and simultaneity.

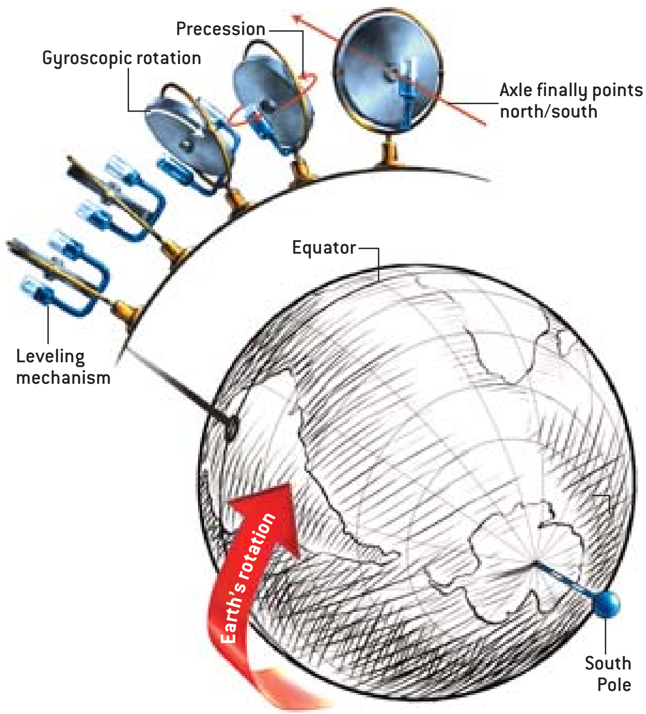
In his 1907 principle of equivalence, Einstein had objected to the previously unchallenged claim that there were two kinds of mass—gravitational mass (responsible for the weight of a lead ball) and inertial mass (the resistance of a mass, say a lead ball, to acceleration, even far out in space). Instead Einstein stated that there was just one kind of mass. There was no way to distinguish the behavior of mass pressed to the floor of an accelerating rocket ship and that of mass pulled to the floor of a stationary room in a gravitational field.

So Einstein likewise believed deeply that there was but one kind of magnetism and that it was caused by the aligned orientation of tiny magnets—current loops formed by electrons as they raced around atomic nuclei. The question was: How could one test this idea?

Suppose that you are standing on a lazy Susan with a gyroscope in each hand, each with its axis pointing away from you and spinning clockwise from your point of view. The gyroscopes' angular momenta are oriented in opposite directions, so the system's total angular momentum adds to zero. Next, say you raise your hands above your head so the gyroscopes are now both pointing up. This means their angular momenta are both aimed in the same direction, so they sum to a nonzero value. But because the angular momentum in a closed system is conserved (stays the same), you begin to rotate on the lazy Susan, in this case to counter the angular momenta of the gyros.

Einstein imagined this scenario in miniature, inside an iron bar. Suppose that an unmagnetized iron cylinder was suspended by a fine, flexible fiber [*see illustration on opposite page*] and that suddenly a strong magnetic field was applied, enough to magnetize the cylinder by orienting all the little electron orbits. If he was correct, many of the little randomly oriented electron orbits would then be aligned. Their angular momenta would suddenly add instead of canceling. And again, just as the lazy Susan did, the cylinder would rotate to compensate. This was the notion behind the experiment. In time, amazingly, Einstein and de Haas succeeded in eliciting results from the remarkably delicate apparatus they built subsequently. But from where did this concept come, and why just then in 1915, amid the worst war and his own high-stakes struggle to define general relativity?

For an answer, one must look back to the period after Einstein's graduation from the Zurich Polytechnic in 1900, years during which he found it difficult to find gainful employment. Rejection letters piled up until mid-1902, when he finally received a very welcome job offer from the Bern Patent Office. Although Einstein had battled with one teacher after another during his school years, he admired and learned much from the head of the patent office, Friedrich Haller. Einstein learned




GYROCOMPASSES use forces generated by the earth's rotation to locate north regardless of position on the globe. Early Anschütz-Kaempfe design is weighted so that gravity keeps it level. As the planet turns, the spinning gyro axle also rotates along with the surface of the earth. Because the gyro tries to hold itself level, the result is precession, an effect that moves the gyro's axle at a right angle to the applied force; the phenomenon is akin to that seen when a child's top wobbles as it slows. Precession eventually leads the axle to point north (*images left to right*).

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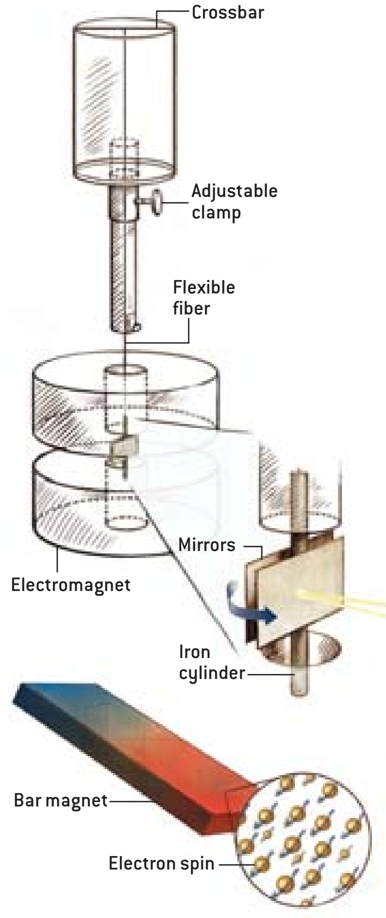
to adhere strictly to Haller's injunction to "remain critically vigilant"—to view inventors' claims with skepticism.




EXPERIMENTAL APPARATUS that Einstein and de Haas used to prove their theory explaining the magnetism of iron is shown. They suspended an unmagnetized iron cylinder by a flexible fiber and then applied a strong magnetic field. According to their theory, the cylinder would rotate because the field would align the orbits of electrons inside. Mirrors attached to the cylinder (*detail*) reflected a light beam as it turned—providing proof of their theory. It was later determined that electron spin (rotation in place), not electron orbits, produced the magnetism in iron. A bar magnet, for example, is magnetic because the spins of its electrons line up (*bottom*).

Einstein loved machines and corresponded with other enthusiasts about them; he even built new ones in his apartment. Over the years he patented refrigerators, invented new electrical measurement devices and advised his friends about machinery. Indeed, his father and uncle had long run an electrotechnical business and had patented their own inventions. Sadly for us, nearly all of Einstein's patent evaluations were, by law, destroyed, but a few remain—in particular, those that made their way into court proceedings. That is because Einstein soon became one of the most esteemed technical authorities in the patent office and thus a much appreciated expert witness.

Herein lies the key to understanding Einstein's fascination with magnetism. In the early 20th century the tried-and-true magnetic compass began to suffer difficulties. It worked poorly on new ships, which were becoming metallic and electrified, and functioned badly inside submarines or near the earth's poles. And the standard compass was problematic in aircraft because its directional indicator led and lagged during turns.

Two companies took up the compass problem, one headed by American inventor and industrialist Elmer A. Sperry and the other by his German archrival, Hermann Hubertus Maria Anschütz-Kaempfe. The solution was to convert powered gyroscopes into compasses. Anschütz-Kaempfe cleverly built the casing of his gyroscope so that it would precess (slowly cycle its axial orientation) in such a way that its axis lined up with the rotational axis of the earth [*see illustrations on opposite page*]. Soon afterward, Sperry produced a similar instrument. Anschütz-Kaempfe promptly sued for patent infringement. Sperry mounted the usual defense: he was merely following an older, preexisting idea.

In mid-1915 Einstein was called in to serve as an expert witness. His testimony showed, to the court's satisfaction, that the earlier gimbaled gyroscopes could not possibly have worked as compasses, because they were designed to move only within a very tight range inside their casings—a ship's slightest pitch and yaw would render them useless. Anschütz-Kaempfe won the case. Einstein went on to become sufficiently expert in gyrocompass technology to collect royalties for his work in this field for decades to come.

Einstein's royalties in the science of physics proved to be even greater, however: "I was led to the demonstration of the nature of the paramagnetic atom through technical reports I had prepared on the gyromagnetic compass" [Einstein to E. Meyerson, January 27, 1930, Einstein Archives Online]. He saw that just as the earth's rotation oriented a gyrocompass, a cylinder of iron could be made to rotate by orienting all the little atomic gyroscopes inside it. The experiment turned out to be a spectacular success [*see illustration at left*]. Einstein and de Haas had demonstrated an effect so subtle that even the great James Clerk Maxwell had failed to discern it.

But this story has a twist. The two physicists showed excellent agreement between the theory (ferromagnetism caused by orbiting electrons) and their experiment. Unfortunately, their striking result soon came under attack—cautiously at first, then with growing insistence. It seemed that their measurement of magnetism per unit of angular momentum was off by a factor of two, a difference no one could adequately explain until much later, after the development of quantum mechanics and the concept of electron spin. It seems that Einstein's commitment to a particular theoretical model had cut two ways. On the one hand, it had given him real conviction about how to organize and conduct the experiment—specifically, where to look for the effect. Maxwell and others who had failed before had no feeling for the magnitude of the phenomenon. On the other hand, the theoretical model Einstein chose made it easy to accept an experimental answer when blackboard calculation and laboratory results agreed—despite the existence of many potentially interfering factors, which included such things as the effect of the earth's magnetic field and the vagaries of the fragile lab apparatus itself.

The tale reminds me of one of Einstein's wonderful sayings: "No one but a theorist believes his theory; everyone puts faith in a laboratory result but the experimenter himself." SA

## MORE TO EXPLORE

A more detailed study of Einstein's patent work and experiment can be found in Galison's *How Experiments End* (University of Chicago Press, 1987).

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