

causality were suspect to him, mere habits of the mind; a ball hitting another may behave the way that Newton's laws predict time after time after time, yet that was not, strictly speaking, a reason to believe that it would happen that way the next time. "Hume saw clearly that certain concepts, for example that of causality, cannot be deduced from our perceptions of experience by logical methods," Einstein noted.

A version of this philosophy, sometimes called positivism, denied the validity of any concepts that went beyond descriptions of phenomena that we directly experience. It appealed to Einstein, at least initially. "The theory of relativity suggests itself in positivism," he said. "This line of thought had a great influence on my efforts, most specifically Mach and even more so Hume, whose *Treatise of Human Nature* I studied avidly and with admiration shortly before discovering the theory of relativity."⁸¹

Hume applied his skeptical rigor to the concept of time. It made no sense, he said, to speak of time as having an absolute existence that was independent of observable objects whose movements permitted us to define time. "From the succession of ideas and impressions we form the idea of time," Hume wrote. "It is not possible for time alone ever to make its appearance." This idea that there is no such thing as absolute time would later echo in Einstein's theory of relativity. Hume's specific thoughts about time, however, had less influence on Einstein than his more general insight that it is dangerous to talk about concepts that are not definable by perceptions and observations.⁸²

Einstein's views on Hume were tempered by his appreciation for Immanuel Kant (1724–1804), the German metaphysician he had been introduced to, back when he was a schoolboy, by Max Talmud. "Kant took the stage with an idea that signified a step towards the solution of Hume's dilemma," Einstein said. Some truths fit into a category of "definitely assured knowledge" that was "grounded in reason itself."

In other words, Kant distinguished between two types of truths: (1) analytic propositions, which derive from logic and "reason itself" rather than from observing the world; for example, all bachelors are unmarried, two plus two equals four, and the angles of a triangle always add up to 180 degrees; and (2) synthetic propositions, which are based on experience and observations; for example, Munich is bigger than

Bern, all swans are white. Synthetic propositions could be revised by new empirical evidence, but not analytic ones. We may discover a black swan but not a married bachelor or (at least so Kant thought) a triangle with 181 degrees. As Einstein said of Kant's first category of truths: "[This is held to be the case, for example, in the propositions of geometry and in the principle of causality. These and certain other types of knowledge . . . do not previously have to be gained from sense data, in other words they are a priori knowledge.]"

Einstein initially found it wondrous that certain truths could be discovered by reason alone. But he soon began to question Kant's rigid distinction between analytic and synthetic truths. "The objects with which geometry deals seemed to be of no different type than the objects of sensory perception," he recalled. And later he would reject outright this Kantian distinction. "I am convinced that this differentiation is erroneous," he wrote. A proposition that seems purely analytic—such as the angles of a triangle adding up to 180 degrees—could turn out to be false in a non-Euclidean geometry or in a curved space (such as would be the case in the general theory of relativity). As he later said of the concepts of geometry and causality, "Today everyone knows, of course, that the mentioned concepts contain nothing of the certainty, of the inherent necessity, which Kant had attributed to them."⁸³

Hume's empiricism was carried a step further by Ernst Mach (1838–1916), the Austrian physicist and philosopher whose writings Einstein read at the urging of Michele Besso. He became one of the favorite authors of the Olympia Academy, and he helped to instill in Einstein the skepticism about received wisdom and accepted conventions that would become a hallmark of his creativity. Einstein would later proclaim, in words that could be used to describe himself as well, that Mach's genius was partly due to his "incorruptible skepticism and independence."⁸⁴

The essence of Mach's philosophy was this, in Einstein's words: "Concepts have meaning only if we can point to objects to which they refer and to the rules by which they are assigned to these objects."⁸⁵ In other words, for a concept to make sense you need an operational definition of it, one that describes how you would observe the concept in operation. This would bear fruit for Einstein when, a few years later, he

Wresting Principles from Nature

In his more radical salad days, Einstein did not emphasize this credo. He had instead cast himself as an empiricist or positivist. In other words, he had accepted the works of Hume and Mach as sacred texts, which led him to shun concepts, like the ether or absolute time, that were not knowable through direct observations.

Now, as his opposition to the concept of an ether became more subtle and his discomfort with quantum mechanics grew, he edged away from this orthodoxy. "What I dislike in this kind of argumentation," the older Einstein reflected, "is the basic positivistic attitude, which from my point of view is untenable, and which seems to me to come to the same thing as Berkeley's principle, *Esse est percipi*."³⁸

There was a lot of continuity in Einstein's philosophy of science, so it would be wrong to insist that there was a clean shift from empiricism to realism in his thinking.³⁹ Nonetheless, it is fair to say that as he struggled against quantum mechanics during the 1920s, he became less faithful to the dogma of Mach and more of a realist, someone who believed, as he said in his tribute to Maxwell, in an underlying reality that exists independently of our observations.

That was reflected in a lecture that Einstein gave at Oxford in June 1933, called "On the Method of Theoretical Physics," which sketched out his philosophy of science.⁴⁰ It began with a caveat. To truly understand the methods and philosophy of physicists, he said, "don't listen to their words, fix your attention on their deeds."

If we look at what Einstein did rather than what he was saying, it is clear that he believed (as any true scientist would) that the end product of any theory must be conclusions that can be confirmed by experience and empirical tests. He was famous for ending his papers with calls for these types of suggested experiments.

But how did he come up with the starting blocks for his theoretical

³⁸ "To be is to be perceived," meaning that it makes no sense to say that unperceived things—most famously Berkeley's example of trees in a forest "and no body by to perceive them"—actually exist (George Berkeley, *Principles of Human Knowledge*, section 23).

thinking—the principles and postulates that would launch his logical deductions? As we've seen, he did not usually start with a set of experimental data that needed some explanation. "No collection of empirical facts, however comprehensive, can ever lead to the formulation of such complicated equations," he said in describing how he had come up with the general theory of relativity.⁴¹ In many of his famous papers, he made a point of insisting that he had not relied much on any specific experimental data—on Brownian motion, or attempts to detect the ether, or the photoelectric effect—to induce his new theories.

Instead, he generally began with postulates that he had abstracted from his understanding of the physical world, such as the equivalence of gravity and acceleration. That equivalence was not something he came up with by studying empirical data. Einstein's great strength as a theorist was that he had a keener ability than other scientists to come up with what he called "the general postulates and principles which serve as the starting point."

It was a process that mixed intuition with a feel for the patterns to be found in experimental data. "The scientist has to worm these general principles out of nature by discerning, when looking at complexes of empirical facts, certain general features."⁴² When he was struggling to find a foothold for a unified theory, he captured the essence of this process in a letter to Hermann Weyl: "I believe that, in order to make any real progress, one would again have to find a general principle wrested from Nature."⁴³

Once he had wrested a principle from nature, he relied on a byplay of physical intuition and mathematical formalism to march toward some testable conclusions. In his younger days, he sometimes disparaged the role that pure math could play. But during his final push toward a general theory of relativity, it was the mathematical approach that ended up putting him across the goal line.

From then on, he became increasingly dependent on mathematical formalism in his pursuit of a unified field theory. "The development of the general theory of relativity introduced Einstein to the power of abstract mathematical formalisms, notably that of tensor calculus," writes the astrophysicist John Barrow. "A deep physical insight orchestrated the mathematics of general relativity, but in the years that followed the

balance tipped the other way. Einstein's search for a unified theory was characterized by a fascination with the abstract formalisms themselves."⁴⁴

In his Oxford lecture, Einstein began with a nod to empiricism: "All knowledge of reality starts from experience and ends in it." But he immediately proceeded to emphasize the role that "pure reason" and logical deductions play. He conceded, without apology, that his success using tensor calculus to come up with the equations of general relativity had converted him to a faith in a mathematical approach, one that emphasized the simplicity and elegance of equations more than the role of experience.

The fact that this method paid off in general relativity, he said, "justifies us in believing that *nature is the realization of the simplest conceivable mathematical ideas.*"⁴⁵ That is an elegant—and also astonishingly interesting—creed. It captured the essence of Einstein's thought during the decades when mathematical "simplicity" guided him in his search for a unified field theory. And it echoed the great Isaac Newton's declaration in book 3 of the *Principia*: "Nature is pleased with simplicity."

But Einstein offered no proof of this creed, one that seems belied by modern particle physics.⁴⁶ Nor did he ever fully explain what, exactly, he meant by mathematical simplicity. Instead, he merely asserted his deep intuition that this is the way God would make the universe. "I am convinced that we can discover by means of purely mathematical constructions the concepts and the laws connecting them with each other," he claimed.

It was a belief—indeed, a faith—that he had expressed during his previous visit to Oxford, when in May 1931 he had been awarded an honorary doctorate there. In his lecture on that occasion, Einstein explained that his ongoing quest for a unified field theory was propelled by the lure of mathematical elegance, rather than the push of experimental data. "I have been guided not by the pressure from behind of experimental facts, but by the attraction in front from mathematical simplicity," he said. "It can only be hoped that experiments will follow the mathematical flag."⁴⁷

Einstein likewise concluded his 1933 Oxford lecture by saying that he had come to believe that the mathematical equations of field theo-

ries were the best way to grasp "reality." So far, he admitted, this had not worked at the subatomic level, which seemed ruled by chance and probabilities. But he told his audience that he clung to the belief that this was not the final word. "I still believe in the possibility of a model of reality—that is to say, of a theory that represents things themselves and not merely the probability of their occurrence."⁴⁸

His Greatest Blunder?

Back in 1917, when Einstein had analyzed the "cosmological considerations" arising from his general theory of relativity, most astronomers thought that the universe consisted only of our Milky Way, floating with its 100 billion or so stars in a void of empty space. Moreover, it seemed a rather stable universe, with stars meandering around but not expanding outward or collapsing inward in a noticeable way.

All of this led Einstein to add to his field equations a cosmological constant that represented a "repulsive" force (see page 254). It was invented to counteract the gravitational attraction that would, if the stars were not flying away from one another with enough momentum, pull all of them together.

Then came a series of wondrous discoveries, beginning in 1924, by Edwin Hubble, a colorful and engaging astronomer working with the 100-inch reflector telescope at the Mount Wilson Observatory in the mountains above Pasadena, California. The first was that the blur known as the Andromeda nebula was actually another galaxy, about the size of our own, close to a million light years away (we now know it's more than twice that far). Soon he was able to find at least two dozen even more distant galaxies (we now believe that there are more than 100 billion of them).

Hubble then made an even more amazing discovery. By measuring the red shift of the stars' spectra (which is the light wave counterpart to the Doppler effect for sound waves), he realized that the galaxies were moving away from us. There were at least two possible explanations for the fact that distant stars in all directions seemed to be flying away from us: (1) because we are the center of the universe, something that since the time of Copernicus only our teenage children believe; (2) be-

ables and ignore (or average over) the rest. These “decoherent” histories form a tree-like structure, with each of the alternatives at one time branching out into alternatives at the next time and so forth.

In the case of the EPR thought experiment, the position of one of the two particles is measured on one branch of history. Because of the common origin of the particles, the position of the other one is determined as well. On a different branch of history, the momentum of one of the particles may be measured, and the momentum of the other one is also determined. On each branch nothing occurs that violates the laws of classical physics. The information about one particle *implies* the corresponding information about the other one, but nothing *happens* to the second particle as a result of the measurement of the first one. So there is no threat to special relativity and its prohibition of instantaneous transmission of information. What is special about quantum mechanics is that the simultaneous determination of the position and the momentum of a particle is impossible, so if these two determinations occur, it must be on different branches of history.³⁵

“Physics and Reality”

Einstein’s fundamental dispute with the Bohr-Heisenberg crowd over quantum mechanics was not merely about whether God rolled dice or left cats half dead. Nor was it just about causality, locality, or even completeness. It was about reality.³⁶ Does it exist? More specifically, is it meaningful to speak about a physical reality that exists independently of whatever observations we can make? “At the heart of the problem,” Einstein said of quantum mechanics, “is not so much the question of causality but the question of realism.”³⁷

Bohr and his adherents scoffed at the idea that it made sense to talk about what might be beneath the veil of what we can observe. All we can know are the results of our experiments and observations, not some ultimate reality that lies beyond our perceptions.

Einstein had displayed some elements of this attitude in 1905, back when he was reading Hume and Mach while rejecting such unobservable concepts as absolute space and time. “At that time my mode of thinking was much nearer positivism than it was later on,” he recalled.

“My departure from positivism came only when I worked out the general theory of relativity.”³⁸

From then on, Einstein increasingly adhered to the belief that there is an objective classical reality. And though there are some consistencies between his early and late thinking, he admitted freely that, at least in his own mind, his realism represented a move away from his earlier Machian empiricism. “This credo,” he said, “does not correspond with the point of view I held in younger years.”³⁹ As the historian Gerald Holton notes, “For a scientist to change his philosophical beliefs so fundamentally is rare.”⁴⁰

Einstein’s concept of realism had three main components:

1. His belief that a reality exists independent of our ability to observe it. As he put it in his autobiographical notes: “Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed. In this sense one speaks of ‘physical reality.’”⁴¹
2. His belief in separability and locality. In other words, objects are located at certain points in spacetime, and this separability is part of what defines them. “If one abandons the assumption that what exists in different parts of space has its own independent, real existence, then I simply cannot see what it is that physics is supposed to describe,” he declared to Max Born.⁴²
3. His belief in strict causality, which implies certainty and classical determinism. The idea that probabilities play a role in reality was as disconcerting to him as the idea that our observations might play a role in collapsing those probabilities. “Some physicists, among them myself, cannot believe,” he said, “that we must accept the view that events in nature are analogous to a game of chance.”⁴³

It is possible to imagine a realism that has only two, or even just one, of these three attributes, and on occasion Einstein pondered such a possibility. Scholars have debated which of these three was most fundamental to his thinking.⁴⁴ But Einstein kept coming back to the hope, and faith, that all three attributes go together. As he said in a speech to

a doctors convention in Cleveland near the end of his life, "Everything should lead back to conceptual objects in the realm of space and time and to lawlike relations that obtain for these objects."⁴⁵

At the heart of this realism was an almost religious, or perhaps childlike, awe at the way all of our sense perceptions—the random sights and sounds that we experience every minute—fit into patterns, follow rules, and make sense. We take it for granted when these perceptions piece together to represent what seem to be external objects, and it does not amaze us when laws seem to govern the behavior of these objects.

But just as he felt awe when first pondering a compass as a child, Einstein was able to feel awe that there are rules ordering our perceptions, rather than pure randomness. Reverence for this astonishing and unexpected comprehensibility of the universe was the foundation for his realism as well as the defining character of what he called his religious faith.

He expressed this in a 1936 essay, "Physics and Reality," written on the heels of his defense of realism in the debates over quantum mechanics. "The very fact that the totality of our sense experiences is such that, by means of thinking, it can be put in order, this fact is one that leaves us in awe," he wrote. "The eternal mystery of the world is its comprehensibility . . . The fact that it is comprehensible is a miracle."⁴⁶

His friend Maurice Solovine, with whom he had read Hume and Mach in the days of the Olympia Academy, told Einstein that he found it "strange" that he considered the comprehensibility of the world to be "a miracle or an eternal mystery." Einstein countered that it would be logical to assume that the opposite was the case. "Well, a priori, one should expect a chaotic world which cannot be grasped by the mind in any way," he wrote. "There lies the weakness of positivists and professional atheists."⁴⁷ Einstein was neither.

To Einstein, this belief in the existence of an underlying reality had a religious aura to it. That dismayed Solovine, who wrote to say that he had an "aversion" to such language. Einstein disagreed. "I have no better expression than 'religious' for this confidence in the rational nature of reality and in its being accessible, to some degree, to human reason.

When this feeling is missing, science degenerates into mindless empiricism."⁴⁸

Einstein knew that the new generation viewed him as an out-of-touch conservative clinging to the old certainties of classical physics, and that amused him. "Even the great initial success of the quantum theory does not make me believe in a fundamental dice-game," he told his friend Max Born, "although I am well aware that our younger colleagues interpret this as a consequence of senility."⁴⁹

Born, who loved Einstein dearly, agreed with the Young Turks that Einstein had become as "conservative" as the physicists of a generation earlier who had balked at his relativity theory. "He could no longer take in certain new ideas in physics which contradicted his own firmly held philosophical convictions."⁵⁰

But Einstein preferred to think of himself not as a conservative but as (again) a rebel, a nonconformist, one with the curiosity and stubbornness to buck prevailing fads. "The necessity of conceiving of nature as an *objective reality* is said to be obsolete prejudice while the quantum theoreticians are vaunted," he told Solovine in 1938. "Each period is dominated by a mood, with the result that most men fail to see the tyrant who rules over them."⁵¹

Einstein pushed his realist approach in a textbook on the history of physics that he coauthored in 1938, *The Evolution of Physics*. Belief in an "objective reality," the book argued, had led to great scientific advances throughout the ages, thus proving that it was a useful concept even if not provable. "Without the belief that it is possible to grasp reality with our theoretical constructions, without the belief in the inner harmony of our world, there could be no science," the book declared. "This belief is and always will remain the fundamental motive for all scientific creation."⁵²

In addition, Einstein used the text to defend the utility of field theories amid the advances of quantum mechanics. The best way to do that was to view particles not as independent objects but as a special manifestation of the field itself:

There is no sense in regarding matter and field as two qualities quite different from each other . . . Could we not reject the concept of matter and build a pure field physics? We could regard matter as the regions in