Einstein and Newton:

TWO LEGACIES

Albert Einstein was born in Ulm, Germany, the son of a factory owner, on March 14, 1879. Centennial celebrations are planned around the world. Einstein's most revolutionary work, contained in a handful of articles, was published before he was 40; in his last decades, however, he shunned the quantum mechanics he had helped to develop. Why? Part of the answer can be gleaned from a 1927 essay he wrote for the *Manchester Guardian* on the bicentennial of Isaac Newton's death. We reprint it here, annotated and slightly abridged by the editors, following an introduction by the Smithsonian Institution's Paul Forman.

by Paul Forman

Albert Einstein composed tributes to many individuals but to only three men he had never met—Johannes Kepler (d. 1630), who formulated the laws of planetary motion; Isaac Newton (d. 1727), who derived those laws from general dynamic principles and a law of universal gravitation; and James Clerk Maxwell (d. 1879), who, by a mathematical formulation of Michael Faraday's concept of a physical state pervading all matter and space (a "field"), obtained the laws of electromagnetism. For Einstein, these three men defined the enterprise he adopted as his own life's work: the construction of a *complete* description of physical reality using the concepts of space, time, force, material point (matter), and continuous field.

Of these three men, it was Newton whom Einstein regarded as the father of theoretical physics. For it was Newton who invented differential calculus and thus laid the foundations of a mechanics providing continuous, pictorial, causal descriptions of physical processes. A profound natural philosopher, he brought undreamed of order and interconnection into Nature through his hypothesis of universal gravitation. With a single mathematical law, he accounted for the tides, the motion of objects on earth, and the paths of bodies in the heavens. And yet—and this especially excited Einstein's admiration—Newton was not so blinded by the brilliance of his achievement that he overlooked the logical and metaphysical weaknesses of his own mechanical axioms and physical hypotheses.

Still, Einstein, intent upon seeing in Newton the origins of his own scientific goals and tools, attributed to his hero much that does not fit the historical person. In his 1927 essay, he misrepresents Newton most seriously by attributing to him his own, deterministic belief that the entire future evolution of the universe could be calculated given its configuration and motion at any given moment. So rigorous an exclusion of God from any further influence upon the world He had created was, to Newton's mind, too close to atheism.

Spraining the Brain

Nor did Einstein appreciate how extremely different Newton's personality and values were from his own. Newton largely neglected the mathematical physics for which he was uniquely suited, devoting himself instead to intellectually less demanding investigations, such as Biblical chronology. In 1695, at the age of 53, Newton obtained appointment as Master of the Mint and abandoned his scholarly life in Cambridge for the bustle of London. Einstein, by contrast, never shirked the extraordinarily difficult assignment he had given himself. Nor did he bolster himself with romantic illusions about the nature of that task: "He who knows the pleasures of intellectual work does not go chasing after it," he often remarked. But an unceasing "spraining of the brain," he would add, was the fate of "a man of my type."

In their relations with people, too, Einstein and Newton could scarcely have been less alike. The Briton was celibate, secretive, vindictive, variously fawning or haughty, tolerant only of sycophants—in short, a cold and unattractive personality. Einstein, on the other hand, at least in his mature years, displayed the greatest warmth, gentleness, openness to criti-

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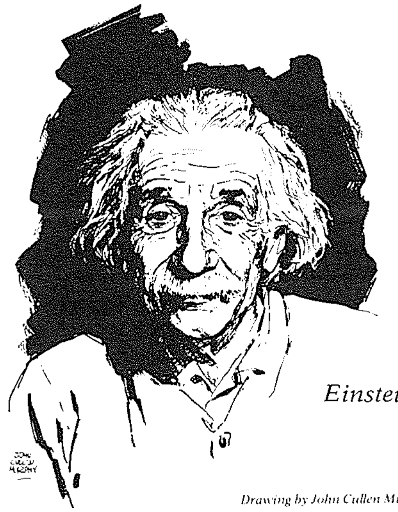


Einstein at age 70.

Drawing by John Cullen Murphy.

cism, disregard for social rank and convention, and the deepest concern for humanity. Only with his fellow physicists was Einstein's tone a bit impatient, ironic, mocking. Only from them did he *expect* something, and almost invariably they disappointed him. With his work, they seldom could help; their own seemed largely directed by academic fashion and opportunism.

As a theoretical physicist, Einstein was almost entirely self-taught. His formal higher education was limited to a four-year course at the Swiss Federal Polytechnic in Zurich, where he was trained as a high school teacher of mathematics and physics. A mediocre student, he neglected his course work (with first-rate scientists) in order to pursue his private study of the classics of theoretical physics, including the works of Gustav Kirchhoff, Hermann Helmholtz, and Heinrich Hertz.

Following graduation in 1900, Einstein lived and worked for nine intensely creative and productive years in a nonacademic environment; most of this time was spent as a patent examiner at the Swiss patent office in Bern. Here the young "Technical Expert, 3rd class" conceived the special theory of relativity (from which he deduced the equivalence of mass and energy, $E=mc^2$); a general statistical mechanics (from which he deduced the laws governing the fluctuations in the motion of a particle suspended in a fluid, and thus made possible the experimental determination of the size of a molecule); and the idea that light really consists of particles, whose behavior is wave-like only on the average (thus explaining the circumstances under which electrons are released from metals by light, and several other puzzling phenomena).

Remarkably, Einstein's first papers on all three subjects appeared not only in a single year—his twenty-seventh, 1905—but also in a single volume of the German journal, *Annalen der Physik.* (Compare Newton, who, in a single fruitful year—his twenty-fourth, 1666—discovered that "white" light is actually a rainbow of colors, invented differential and integral calculus, and worked out the basic laws of mechanics as well as the law of universal gravitation.)

In view of the novelty and ultimate importance of Einstein's ideas, in particular those three which he exposed almost simultaneously in 1905, it would be easy, and it certainly is common, to describe Einstein as a revolutionary in science. Yet, considering the case more closely, a revolutionary guise seems improbable for Einstein, who in these early years was isolated socially and intellectually from his fellow physicists. In fact, while his academic colleagues were behaving like self-conscious revolutionaries—striving to replace the old, mechanistic world view with one founded upon electromagnetism and the newly discovered electron—Einstein sustained himself with the notion that he was within the high tradition of theoretical physics, extending and perfecting the mechanical picture deriving ultimately from Newton. Certainly that was the intent behind his special theory of relativity, which, by obtaining the same results as were derived from the electromagnetic world view, but without any assumptions about the nature of the forces or substances involved, pulled the rug out from under the electromagnetic program.

Philosophically, Einstein was much influenced in these years by Ernst Mach (1836–1916) and Henri Poincaré (1854–1912), who persuasively expressed certain views which were widespread among late 19th- and early 20th-century physicists. Mach and Poincaré emphasized, on the one hand, that only concepts and constructs capable of being defined in terms of sensory experiences—i.e., in terms of possible experiments—were to be admitted into science. On the other hand, they believed, the actual choice of concepts, especially fundamental concepts, was to a large degree arbitrary, a matter of convention. But while his fellow physicists persisted in this view, which they eventually regarded as strikingly confirmed by Einstein's own work, Einstein himself gradually moved "backward" philosophically to the *realist* view that scientific constructs—the conservation of energy, say, or the concept of the atom—approximate entities and connections that really exist.

In one crucial respect, Einstein never deviated from that "outmoded" realist metaphysics, namely, in his adherence to causality. In the years before the First World War, Einstein's contemporaries declared the notion of cause-and-effect to have no place in physics, which, they alleged, dealt only with functional relations. Yet in these years, Einstein framed profound questions and hypotheses based on the idea of causality, believing firmly that the world is *necessarily* thus and not otherwise.

God Doesn't Play Dice

"What is the reason," he was forever asking, "that Nature behaves in this or that way?" And if no sufficient reason was to be found, he said, then Nature's laws must be other than we have supposed. To carry out these logical investigations, Einstein adopted, primarily from Newton, the so-called thought experiment—an experiment conducted only in the mind, using idealized instruments (such as absolutely rigid rods and perfectly accurate clocks)—and made it his characteristic tool of conceptual analysis.

In 1909, Einstein received his first academic appointment; four years later, he was offered the most prestigious and advantageous position in the world of science, the research professorship in the Prussian Academy of Sciences, which he held until the Nazis came to power in 1933. It was, however, with very mixed feelings that, in the spring of 1914, Einstein moved from Zurich to Berlin, to the capital of the country whose citizenship he had deliberately renounced as a youth of 16 and whose social-political system he still disliked. Within a few months, the break-up of his marriage and the outbreak of the First World War would further aggravate his sense of personal isolation. Einstein threw himself into his work and brought the general theory of relativity to completion. The end of the war gave Germany a (short-lived) democratic republic. It also marked the beginning of Einstein's world renown—a result of the confirmation, by British scientists observing the total eclipse of the sun in 1919, of Einstein's prediction that starlight passing close to the sun is deflected by its gravitational field.

Meanwhile, with the end of World War I, there swept over Germany a new romanticism—a "life philosophy" whose most popular prophets were Oswald Spengler, Ludwig Klages, Hermann Keyserling, and Rudolf Steiner. In their view, theoretical physics was the deplorable epitome of Western culture's logical, abstract, unintuitive, and, above all, causal mode of apprehending the world. Surprisingly, many theoretical physicists in

Engraving of Isaac Newton by Sir Godfrey Kneller.

German-speaking Central Europe proved susceptible to this anti-scientific spirit.

The concept of causality at issue in the 1920s, the concept many physicists then wished to banish from science, was not that old-fashioned, metaphysical notion of cause-and-effect which they (excepting Einstein!) had eliminated years before. Rather it was the essential, indeed indispensible, principle of functional relationship, of unambiguous determination of physical events. Causality in this heretofore accepted sense meant lawfulness: A system arranged in a definite way would evolve in a definite way. It meant that experiments can be replicated; that there are fixed rules; that God, in Einstein's celebrated phrase, "doesn't play dice."

As noted, Einstein's opponents, the anticausalist physicists were impelled to a radical departure from the traditional goal of science, not primarily by problems or theories within physics itself but by pressure from the general intellectual environment. Justification of the anticausalist position from within physical theory became possible only in 1925–26 with the development of quantum mechanics. Early in the following year—as Einstein was composing the essay on Newton reprinted here—Werner Heisenberg derived his "uncertainty principle," which denies the possibility of predicting in all detail the results of any experiment.

In this "violent dispute over the significance of the law of causality," as physicist Max Planck described it, it was, by and large, the politically and culturally more "progressive" individuals who followed the fashion of the times, while more conservative figures insisted upon the traditional goals of their discipline. Thus, ironically, Einstein's allies were not his closest personal friends. They included not only Max Planck, whom he respected, but also Wilhelm Wien, whose personality and political views he found distasteful. Indeed, the subject and theme of the opening paragraph of Einstein's essay on Newton are virtually identical with those of several of Wien's popular essays and addresses of the preceding year or two.

In Defense of Reason

Einstein's essay on Newton, then, is only secondarily a tribute to the scientist; it is primarily a reaffirmation of allegiance to the goal of a causal description of Nature. It is the admonition of an avowed causalist to his contemporaries—layman and physicist alike. Thirteen times in less than 3,000 words we read "cause," "causality," or "causation." Fifteen years later, in 1942, when Einstein again wrote on Newton—on the occasion of the tricentenary of his birth—neither "causality" nor any of its variants were cited even once. What had changed? Not Einstein's understanding of the historical Newton—anyway, not significantly—but rather the world in which Einstein lived.

By the end of 1942, Einstein had been in the United States for nine years. In November 1940, as a recently naturalized citizen, he had cast his vote for a third term for Roosevelt. He welcomed America's belated entry into World War II and contributed both his prestige and his scientific knowledge to the war effort. "Causality" seemed a terribly abstract notion compared to the more immediate and comprehensive value, "reason," which was at that hour gravely menaced (as indeed it had been during the entire previous decade) by totalitarian dogma. Thus it was "reason," not "causality" that Einstein chose to defend in his second tribute to Newton.

Perhaps more important, Einstein's essay of 1927 belongs, essentially, to that early, acute phase of the causality crisis before the establishment of the quantum mechanics—a phase of ideological competition characterized by manifestos against causality and exhortations in its favor. In the following years, the Heisenberg-Schrödinger noncausal mechanics proved extraordinarily successful in accounting for physical processes at the atomic level and in withstanding Einstein's most determined efforts, over several years, to find gaps in its logical structure. By 1935, the debate between Einstein and his fellow physicists had shifted to a metaphysical plane. *They* maintained that a theory which accounts for the results of all experiments—as quantum mechanics could—is complete. But Einstein contended that a theory which gives no account of the real world, but only of our imperfect (probabilistic) knowledge of that world, is incomplete.

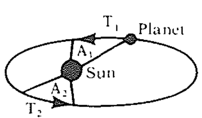
Partly for this reason, the world's most renowned scientist, during the last 20 years of his life, felt almost completely isolated in his scientific work and goals. The situation began to change, however, shortly before Einstein's death in 1955. Today, the subjects of Einstein's own scientific efforts—the general theory of relativity and the unification of the various physical forces (gravitation, electromagnetism, and so on) in a single field theory—have gradually become two of the most important foci of attention in physics.

More to the point of Einstein's 1927 essay, physicists since the early 1950s have been less and less joyful about the indeterminism of our most fundamental theory, more and more ready to declare this feature of quantum mechanics unsatisfactory.

ON NEWTON (1927)

by Albert Einstein

It is just two hundred years ago that Newton closed his eyes. We feel impelled at such a moment to remember this brilliant genius, who determined the course of Western thought, research, and practice like no one else before or since. Destiny placed him at a turning point in the history of the human intellect: Before Newton, there existed no self-contained system of physical causality that was somehow capable of representing any of the deeper features of the empirical world.



If $T_1 = T_2, A_1 = A_2$

Newton's object was to answer the question: Is there any simple rule by which one can calculate the movements of the heavenly bodies in our planetary system completely, when the state of motion of all these bodies at one moment is known? Kepler's empirical laws of planetary movement, deduced from Tycho

Brahe's observations, confronted him and demanded explanation.[1] These laws gave, it is true, a complete answer to the question of *how* the planets move around the sun. But they do not satisfy the demand for causal explanation. More important, these laws are concerned with the movement as a whole, not with the question of how the state of motion of a system gives rise to that which immediately follows it in time. They are, as we would say now, *integral* and not *differential* laws.[2] The differential law is the only form which completely satisfies the modern physicist's demand for causality. The clear conception of the differential law is one of Newton's greatest intellectual achievements.

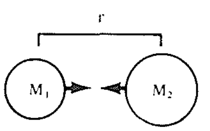
Galileo had already made a significant beginning toward a knowledge of the law of motion. He discovered the law of inertia and the law of bodies falling freely in the gravitational field of the earth (that is, that a mass, or mass-point, unaffected by other masses, will move uniformly and in a straight line; the vertical speed of a free body in the gravitational field increases uniformly with time). It may seem to us today to be but a short step from Galileo's discoveries to Newton's law of motion.[3] But both of Galileo's statements are so formulated as to refer to motion as a whole, while Newton's law of motion provides an answer to the question: How does the state of motion of a mass-point change in an *infinitely short time* under the influence of an external force? It was only by considering what takes place during an infinitely short time (differential law) that Newton reached a formulation that applies to *all* motion. He took the concept of force from the science of statics, which had already reached a high stage of development; he was able to connect force and acceleration by introducing the new concept of mass.

But a causal concept of motion was still far away, for the motion could only be determined from the equation of motion in cases where the force was given. Inspired no doubt by the laws of planetary motion, Newton conceived the idea that the force operating on a mass was determined by the position of all masses situated at a sufficiently small distance from the mass in question. It was not until this connection was established that a completely causal concept of motion was achieved. How Newton, starting from Kepler's laws of planetary motion, performed this task for gravitation and so discovered that gravity and the moving forces acting on the stars were one and the same is well

[1]Kepler's laws: (*a*) planets move in ellipses, with the sun at one focus; (*b*) the radius drawn from the sun to a planet sweeps equal areas in equal times (see diagram); (*c*) the ratio of the cube of the major axis of a planet's elliptical orbit to the square of the period of its revolution around the sun is the same for every planet.

[2]Integration and differentiation, roughly speaking, are inverse operations. That is, where differential calculus can represent motion over an infinitely short period of time, integral calculus represents the *sum* of those infinitely short periods (i.e., total motion).

[3]Newton's law: (*a*) a body will remain at rest or in uniform motion if no force acts on it; (*b*) force = mass X acceleration *(F=ma)*; (*c*) for every force in Nature, there is always an equal and opposite force.



$$F = \frac{Gm_1m_2}{r^2}$$

known.[4] It is the combination

(Law of Motion) + (Law of Attraction)

which constitutes that marvelous edifice of thought that makes it possible to calculate the past and future states of a system from the state obtaining at one particular moment, insofar as the events take place under the influence of the forces of gravity alone. The logical completeness of Newton's conceptual system lay in this, that the only causes of the acceleration of the masses of a system are these masses themselves. On this foundation, Newton succeeded in explaining the motions of the planets, moons, and comets down to the smallest details, as well as the tides and the precessional movement of the earth—a deductive achievement of unique magnificence.

But the importance of Newton's achievement was not limited to the fact that it created a workable and logically satisfactory basis for the actual science of mechanics; up to the end of the 19th century, it formed the program of every worker in the field of theoretical physics. All physical events were to be traced back to masses subject to Newton's laws of motion. The law of force simply had to be extended and adapted to the type of event under consideration. Newton himself tried to apply this program to optics, assuming light to consist of inert corpuscles. Even the wave theory of light made use of Newton's law of motion after it had been applied to continuously distributed masses.[5] Newton's equations of motion were the sole basis of the kinetic theory of heat, which not only prepared people's minds for the discovery of the law of the conservation of energy but also led to a theory of gases that has been confirmed down to the last detail, and to a more profound view of the nature of the second law of thermodynamics. The development of electricity and magnetism has proceeded up to modern times along Newtonian lines. Even the revolution in electrodynamics and optics brought about by Faraday and Maxwell, which formed the first great fundamental advance in theoretical physics since Newton, took place entirely under the aegis of Newton's ideas.

Newton's fundamental principles were so satisfactory from the logical point of view that the impetus to overhaul them could only spring from the demands of empirical fact. Newton himself was better aware of the weaknesses inherent in his intellectual edifice than the generations of learned scientists that followed him. This fact has always aroused my deep admiration, and I should like, therefore, to dwell on it for

[4] Newton showed that Kepler's laws resulted from planets being acted upon by the gravity of the sun. The resulting law of universal gravitation (a particle of matter attracts every other particle of matter with a force proportionate to the product of their masses and inversely proportionate to the square of their distance) also accounts for the motion of the moon and the rate of fall of bodies to earth (see diagram).

[5] If light is propagated as a wave, it was thought, then space must be filled with something to carry those waves. Hence the assumption of a continuous medium, the hypothetical ether.

a moment.

I. Newton's endeavor to represent his system as necessarily conditioned by experience, and to introduce the smallest possible number of concepts not directly referable to empirical objects, is everywhere evident; in spite of this, he set up the concept of absolute space and absolute time. For this, he has often been criticized in recent years. But in this point, Newton is particularly consistent. He had realized that observable geometrical quantities (distances of material points from one another) and their course in time do not completely characterize motion in its physical aspects. In addition to masses and temporally variable distances, there must be something else that determines motion. That "something" he takes to be relation to "absolute space." He is aware that space must possess a kind of physical reality if his laws of motion are to have any meaning, a reality of the same sort as material points and their distances.

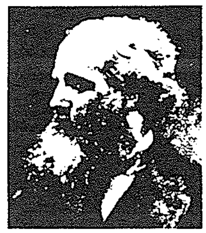
The clear realization of this reveals both Newton's wisdom and also a weak side to his theory. For the logical structure of the latter would undoubtedly be more satisfactory without this shadowy concept; in that case, only things whose relations to perception are perfectly clear (mass-points, distances) would enter into the laws.

II. Forces acting directly and instantaneously at a distance, as introduced to represent the effects of gravity, are not in character with most of the processes familiar to us from everyday life. Newton meets this objection by pointing to the fact that his law of gravitational interaction is not supposed to be a final explanation but a rule derived by induction from experience.

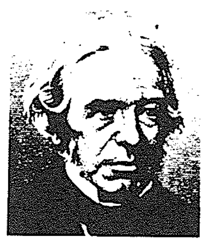
III. Newton's theory provided no explanation for the highly remarkable fact that the weight and the inertia of a body are determined by the same quantity (its mass). Newton himself was aware of the peculiarity of this fact.

None of these three points can rank as a logical objection to the theory. In a sense, they merely represent unsatisfied desires of the scientific mind in its struggle for a complete and uniform conceptual grasp of natural phenomena.

Newton's theory of motion, considered as a program for the whole of theoretical physics, received its first blow from Maxwell's theory of electricity. It became clear that the electric and magnetic interactions between bodies were effected, not by forces operating



James Clerk Maxwell (1831–79).



Michael Faraday (1791–1867)

instantaneously at a distance, but by processes which are propagated through space at a finite speed. In addition to the mass-point and its motion, there arose according to Faraday's concept a new kind of physical reality, namely, the "field."[6] At first, people tried, adhering to the point of view of mechanics, to interpret the field as a mechanical state (of motion or stress) of a hypothetical medium permeating space (ether). But when this interpretation refused to work in spite of the most obstinate efforts, people gradually got used to the idea of regarding the "electromagnetic field" as the final irreducible constituent of physical reality. By the time this point was reached, nobody any longer believed in immediate momentary action at a distance, not even in the realm of gravitation, although no field theory of the latter was clearly indicated owing to lack of sufficient factual knowledge.

The development of the theory of the electromagnetic field led also to the attempt to explain the Newtonian law of motion along electromagnetic lines or to replace it with a more accurate law based on field theory.[7] Even though these efforts did not meet with complete success, the fundamental concepts of mechanics had ceased to be looked upon as fundamental constituents of the physical cosmos.

The theory of Maxwell and Lorentz led inevitably to the special theory of relativity, which, since it abandoned the notion of absolute simultaneity, excluded the existence of forces acting at a distance. It followed from this theory that mass is not a constant quantity but depends on (indeed, is equivalent to) the energy content. It also showed that Newton's law of motion was only to be regarded as a limiting law valid for small velocities; in its place it set up a new law of motion in which the speed of light *in vacuo* figures as the limiting velocity.

The general theory of relativity formed the last step in the development of the program of the field theory.[8] Quantitatively it modified Newton's theory only slightly, but for that all the more profoundly qualitatively. Inertia, gravitation, and the metrical behavior of bodies and clocks were reduced to a single field quality; this field itself was again postulated as dependent on bodies (generalization of Newton's law of gravity or rather the field law corresponding to it, as formulated by Poisson). Space and time were thereby divested not of their reality but of their causal absoluteness. The generalized law of inertia takes over the function of Newton's law of motion.

[6]By *field*, Faraday meant "lines of force" capable of generating action at a distance. The most familiar example would be produced by a magnet.

[7]Einstein alludes here to the electromagnetic world view that arose among physicists after discovery of the electron (1897).

[8]In the General Theory of Relativity, as originally formulated by Einstein: (*a*) Newton's concept of a force acting at a distance was superseded by a description of how a massive body warps space-time in its neighborhood; (*b*) Newton's first law of motion, which determined the path of a particle under the action of the gravitational field, went over into a postulate that such a particle moved not uniformly in a straight line, but along a *geodesic*, the shortest possible line in warped space-time.

This short account is enough to show how the elements of Newtonian theory passed over into the general theory of relativity, whereby the three defects above mentioned were overcome. It looks as if, in the framework of the theory of general relativity, the law of motion could be deduced from the field law corresponding to the Newtonian law of force.[9] Only when this goal has been completely reached will it be possible to talk about a pure field theory.

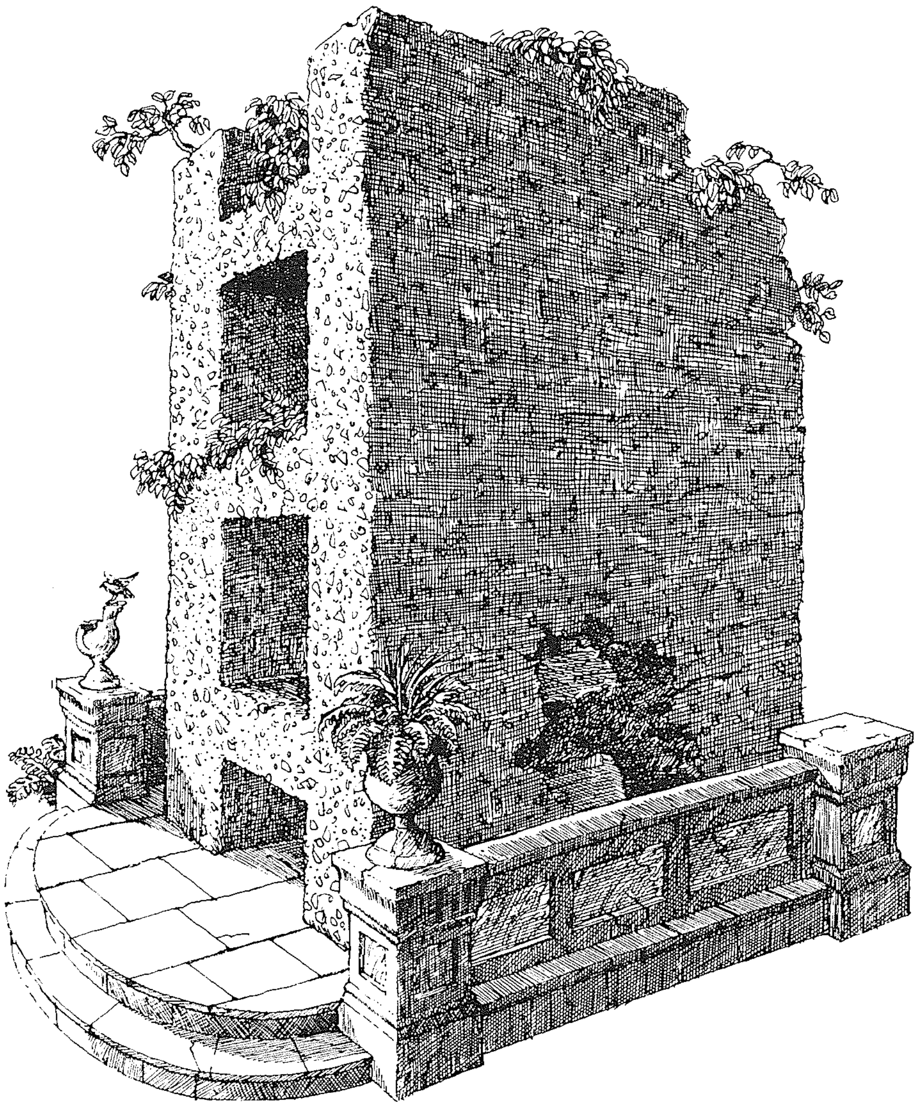
The whole evolution of our ideas about the processes of nature, with which we have been concerned so far, might be regarded as an organic development of Newton's ideas. But while the process of perfecting the field theory was still in full swing, the facts of heat-radiation, the spectra, radioactivity, and so on revealed a limitation of the applicability of this whole conceptual system, which today still seems to us virtually impossible to overcome notwithstanding immense successes in many instances.

Many physicists maintain—and there are weighty arguments in their favor—that in the face of these facts not merely the differential law but the law of causation itself—hitherto the ultimate basic postulate of all natural science—has collapsed. Even the possibility of a spatio-temporal construction, which can be unambiguously coordinated with physical events, is denied. That a mechanical system can have only discrete permanent energy-values or states—as experience almost directly shows—seems at first sight hardly deducible from a field theory that operates with differential equations. The de Broglie–Schrödinger method, which has in a certain sense the character of a field theory, does indeed deduce the existence of only discrete states, in surprising agreement with empirical facts.[10] It does so on the basis of differential equations applying a kind of resonance-argument, but it has to give up the localization of particles and strictly causal laws. Who would presume today to decide the question whether the law of causation and the differential law, these ultimate premises of the Newtonian view of nature, must definitely be abandoned?

[9] Einstein sensed, and 20 years later would prove, that equations of motion in General Relativity were unnecessary: The field equations contain not only the laws of force but also the laws of motion.

[10] Physicists Louis de Broglie and Erwin Schrödinger sought to retain continuity and causality by associating a wave field with every material particle. Max Born, a leader of the anti-causalists, challenged their conclusions, showing that such a field describes not the behavior of individual particles but the statistical distribution of a large number of identical particles under identical conditions.

EDITOR'S NOTE: *The fullest biography of Albert Einstein is Ronald Clark's* Einstein: The Life and Times *(1971). Interested readers may also wish to consult Einstein's own* Ideas and Opinions *(1954).*



From Great Moments in Architecture *by David Macaulay.*

Improvements in building materials, such as steel, glass, and concrete, have allowed architects to erect structures never before thought possible. The results have been mixed. Some modern buildings complement their environments while remaining aesthetic treats in themselves. Others seem to have been conceived by architects bent on erasing the distinction between art and parody.