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INTRODUCTION

I

To anyone familiar with the history of modern science, the phrase "miraculous year" in the title immediately calls to mind its Latin counterpart "annus mirabilis," long used to describe the year 1666, during which Isaac Newton laid the foundations for much of the physics and mathematics that revolutionized seventeenth-century science. It seems entirely fitting to apply the same phrase to the year 1905, during which Albert Einstein not only brought to fruition parts of that Newtonian legacy, but laid the foundations for the break with it that has revolutionized twentieth-century science.

But the phrase was coined without reference to Newton. In a long poem entitled *Annus Mirabilis: The Year of Wonders, 1666*, John Dryden, the famed Restoration poet, celebrated the victory of the English fleet over the Dutch as well as the city of London's survival of the Great Fire. The term was then used to celebrate Newton's scientific activities during the same year—a year in which he laid the foundations of his version of the calculus, his theory of colors, and his theory of gravitation.[1] Here is Newton's own (much later) summary of his accomplishments during this period:

> In the beginning of the year 1665 I found the Method of approximating series & the Rule for reducing any dignity

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> [power] of any Binomial into such a series [i.e., the binomial theorem]. The same year in May I found the method of Tangents . . . , & in November had the direct method of fluxions [i.e., the differential calculus] & the next year in January had the Theory of colours & in May following I had entrance into [th]e inverse method of fluxions [i.e., the integral calculus]. And the same year I began to think of gravity extending to [th]e orb of the Moon & (having found out how to estimate the force with w[hi]ch [a] globe revolving within a sphere presses the surface of a sphere [i.e., the centrifugal force]): from Kepler's rule of the periodical times of the Planets being in sesquialterate proportion of their distances from the centers of their Orbs [i.e., Kepler's third law], I deduced that the forces w[hi]ch keep the Planets in their Orbs must [be] reciprocally as the squares of their distances from the centers about w[hi]ch they revolve: & thereby compared the force requisite to keep the Moon in her Orb with the force of gravity at the surface of the earth, & found them answer pretty nearly. All this was in the two plague years of 1665 & 1666. For in those days I was in the prime of my age for invention & minded Mathematicks & Philosophy more then [*sic*] at any time since.[2]

More recently, the term *annus mirabilis* has been applied to the work of Albert Einstein during 1905 in an effort to establish a parallel between a crucial year in the life of the founding father of classical physics and of his twentieth-century successor.[3] What did Einstein accomplish during his miraculous year? We are fortunate in having his own contemporary summaries of his 1905 papers. Of the first four he wrote to a close friend:

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> I promise you four papers . . . , the first of which I could send you soon, since I will soon receive the free reprints. The paper deals with radiation and the energetic properties of light and is very revolutionary, as you will see. . . . The second paper is a determination of the true sizes of atoms from the diffusion and viscosity of dilute solutions of neutral substances. The third proves that, on the assumption of the molecular [kinetic] theory of heat, bodies of the order of magnitude of 1/1000 mm, suspended in liquids, must already perform an observable random movement that is produced by thermal motion; in fact, physiologists have observed motions of suspended small, inanimate, bodies, which they call "Brownian molecular motion." The fourth paper is only a rough draft at this point, and is an electrodynamics of moving bodies, which employs a modification of the theory of space and time; the purely kinematical part of this paper will surely interest you.[4]

Einstein characterized the fifth paper in these words:

> One more consequence of the paper on electrodynamics has also occurred to me. The principle of relativity, in conjunction with Maxwell's equations, requires that mass be a direct measure of the energy contained in a body; light carries mass with it. A noticeable decrease of mass should occur in the case of radium. The argument is amusing and seductive; but for all I know, the Lord might be laughing over it and leading me around by the nose.[5]

The parallels are clear: each man was in his mid-twenties; each had given little previous sign of the incipient flowering of his genius; and, during a brief time span, each struck

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out on new paths that would ultimately revolutionize the science of his times. If Newton was only twenty-four in 1666 while Einstein was twenty-six in 1905, no one expects such parallels to be perfect.

While these parallels cannot be denied, upon closer inspection we can also see differences—much more significant than the slight disparity in age—between the activities of the two men during their *anni mirabiles* and in the immediate consequences of their work. The first striking difference is the one between their life situations: rejected by the academic community after graduation from the Swiss Polytechnical School in 1900, by 1905 Einstein was already a married man and an active father of a one-year-old son, obliged to fulfill the demanding responsibilities of a full-time job at the Swiss Patent Office. Newton never married (there is speculation that he died a virgin), and he had just taken his bachelor's degree but was still what we would call a graduate student in 1666. Indeed, he had been temporarily freed of even his academic responsibilities by the closure of Cambridge University after outbreaks of the plague.

Next we may note the difference in their scientific standing. Newton had published nothing by 1666, while Einstein already had published five respectable if not extraordinary papers in the prestigious *Annalen der Physik*. Thus, if 1666 marks the year when Newton's genius caught fire and he embarked on independent research, 1905 marks the year when Einstein's already matured talents manifested themselves to the world in a burst of creativity, a series of epoch-making works, all of which were published by the *Annalen* either in that year or the next. None of Newton's activities in 1666 found their way into print until much later: "The first blossoms of his genius flowered in private, observed

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silently by his own eyes alone in the years 1664 to 1666, his *anni mirabiles*."[6] The reasons for Newton's evident lack of a need for recognition—indeed, his pronounced reluctance to share his ideas with others, as his major works had to be pried from his hands by others—have long been the topic of psychological, even psychopathological, speculation.

It took a few years—an agonizingly long time for a young man eager for recognition (see p. 115 below)—for Einstein's achievements to be fully acknowledged by the physics community. But the process started almost immediately in 1905; by 1909 Einstein had been called to a chair of theoretical physics created for him at the University of Zurich, and he was invited to lecture at the annual meeting of the assembled German-speaking scientific community.

Thus, if 1905 marks the beginning of the emergence of Einstein as a leading figure in the physics community, Newton remained in self-imposed obscurity well after 1666. Only in 1669, when at the urging of friends he allowed the limited circulation of a mathematical manuscript divulging some parts of the calculus he had developed, did "Newton's anonymity begin to dissolve."[7]

Another striking difference between the two is in their mathematical talents. Newton manifested his mathematical creativity from the outset. "In roughly a year [1664], without the benefit of instruction, he mastered the entire achievement of seventeenth-century analysis and began to break new ground. . . . The fact that he was unknown does not alter the fact that the young man not yet twenty-four, without benefit of formal instruction, had become the leading mathematician of Europe."[8]

Newton was thus able to create the mathematics necessary to develop his ideas about mechanics and gravitation.

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Einstein, while an able pupil and practitioner, was never really creative in mathematics. Writing about his student years, Einstein said:

> The fact that I neglected mathematics to a certain extent had its cause not merely in my stronger interest in the natural sciences than in mathematics but also in the following peculiar experience. I saw that mathematics was split up into numerous specialties, each of which could easily absorb the short lifetime granted to us. Consequently, I saw myself in the position of Buridan's ass, which was unable to decide upon any particular bundle of hay. Presumably this was because my intuition was not strong enough in the field of mathematics to differentiate clearly the fundamentally important, that which is really basic, from the rest of the more or less dispensable erudition. Also, my interest in the study of nature was no doubt stronger; and it was not clear to me as a young student that access to a more profound knowledge of the more basic principles of physics depends on the most intricate mathematical methods. This dawned upon me only gradually after years of independent scientific work.[9]

Fortunately, for his works of 1905 he needed no more mathematics than he had been taught at school. Even so, it was left to Henri Poincaré, Hermann Minkowski, and Arnold Sommerfeld to give the special theory of relativity its most appropriate mathematical formulation.

When a really crucial need for new mathematics manifested itself in the course of his work on the general theory of relativity, Einstein had to make do with the tensor calculus as developed by Gregorio Ricci-Curbastro and Tullio Levi-Civita and presented to Einstein by his friend and colleague, Marcel Grossmann. This was based on Riemannian

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geometry, which lacked the concepts of parallel displacement and affine connection that would have so facilitated Einstein's work. But he was incapable of filling this mathematical lacuna, a task that was accomplished by Levi-Civita and Hermann Weyl only after the completion of the general theory.

Returning to Newton: in some respects he was right to hesitate about publication in 1666. "When 1666 closed, Newton was not in command of the results that have made his reputation deathless, not in mathematics, not in mechanics, not in optics. What he had done in all three was to lay foundations, some more extensive than others, on which he could build with assurance, but nothing was complete at the end of 1666, and most were not even close to complete."[10]

His work on the method of fluxions (as he called the calculus), even if incomplete, was worthy of publication and would have been of great service to contemporary mathematicians had it been available to them. His work in physics was far less advanced. His experiments on the theory of colors were interrupted by the closing of the university, and after his return to Cambridge in 1667 he spent a decade pursuing his optical investigations. Nevertheless, a more outgoing man might have published a preliminary account of his theory of colors in 1666. But in the case of gravitation, after carefully reviewing the evidence bearing on Newton's work on this subject through 1666, the physicist Leon Rosenfeld concluded that "it will be clear to every scientist that Newton at this stage had opened up for himself an exciting prospect, but had nothing fit to be published."[11] It is also clear that, in thinking about mechanics, he had not yet arrived at a clear concept of force—an essential prerequisite

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for the development of what we now call Newtonian mechanics. He had given "a new definition of force in which a body was treated as the passive subject of external forces impressed upon it instead of the active vehicle of forces impinging on others." But: "More than twenty years of patient if intermittent thought would in the end elicit his whole dynamics from this initial insight."[12]

To sum up, in the case of Newton, in 1666 we have a student, working at his leisure, a mature genius in mathematics, but whose work in physics, however genial, was still in its formative stages. In the case of Einstein, in 1905 we have a man raising a family and pursuing a practical career, forced to fit physics into the interstices of an already-full life, yet already a master of theoretical physics ready to demonstrate that mastery to the world.

II

Newton's great legacy was his advancement of what at the time was called the mechanical philosophy and later came to be called the mechanical worldview. In physics, it was embodied in the so-called central force program: matter was assumed to be made up of particles of different species, referred to as "molecules." Two such molecules exerted various forces on each other: gravitational, electrical, magnetic, capillary, etc. These forces—attractive or repulsive—were assumed to be central, that is, to act in the direction of the line connecting the two particles, and to obey appropriate laws (such as the inverse square law for the gravitational and electrostatic forces), which depended on the distance between them. All physical phenomena were assumed to be

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explicable on the basis of Newton's three laws of motion applied to molecules acted upon by such central forces.

The central force program was shaken around the middle of the nineteenth century when it appeared that, in order to explain electromagnetic interactions between moving charged molecules, velocity- and acceleration-dependent forces had to be assumed. But it received the coup de grâce when Michael Faraday and James Clerk Maxwell's concept of the electromagnetic field began to prevail. According to the field point of view, two charged particles do not interact directly: each charge creates fields in the space surrounding it, and it is these fields which exert forces on the other charge. At first, these electric and magnetic fields were conceived of as states of a mechanical medium, the electromagnetic ether; these states were assumed ultimately to be explainable on the basis of mechanical models of that ether. Meanwhile, Maxwell's equations gave a complete description of the possible states of the electric and magnetic fields at all points of space and how they change over time. By the turn of the century, the search for mechanical explanations of the ether had been largely abandoned in favor of Hendrik Antoon Lorentz's viewpoint, frankly dualistic: the electric and magnetic fields were accepted as fundamental states of the ether, governed by Maxwell's equations but not in need of further explanation. Charged particles, which Lorentz called electrons (others continued to call them molecules or ions), obeyed Newton's mechanical laws of motion under the influence of forces that include the electric and magnetic forces exerted by the ether; and in turn the charged particles created these fields by their presence in and motion through the ether.

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I call Lorentz's outlook dualistic because he accepted the mechanical worldview as applied to his electrons but regarded the ether with its electric and magnetic fields as an additional, independent element of reality, not mechanically explicable. To those brought up on the doctrine of the essential unity of nature, especially popular in Germany since the time of Alexander von Humboldt, such a dualism was uncomfortable if not intolerable.

Indeed, it was not long before Wilhelm Wien and others suggested another possibility: perhaps the electromagnetic field is the really fundamental entity, and the behavior of matter depends entirely on its electromagnetic properties. Instead of explaining the behavior of electromagnetic fields in terms of a mechanical model of the ether, this electromagnetic worldview hoped to explain the mechanical properties of matter in terms of electric and magnetic fields. Even Lorentz flirted with this possibility, though he never fully adopted it.

The mechanical worldview did not simply disappear with the advent of Maxwell's electrodynamics. The last third of the nineteenth century saw a remarkable new triumph of the mechanical program. On the basis of the application of statistical methods to large assemblies of molecules (Avogadro's number, about 6.3×10^{23} molecules per mole of any substance, here gives the measure of largeness), Maxwell and Ludwig Boltzmann succeeded in giving a mechanical foundation to the laws of thermodynamics and started the program of explaining the bulk properties of matter in terms of kinetic-molecular theories of the gaseous, liquid, and solid states.

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III

Thus, as a student Einstein had to master both the traditional mechanical viewpoint, particularly its application to the atomistic picture of matter, as well as Maxwell's new field-theoretical approach to electromagnetism, particularly in Lorentz's version. He was also confronted with a number of new phenomena, such as black-body radiation and the photoelectric effect, which stubbornly resisted all attempts to fit them into either the old mechanical or the new electromagnetic worldview—or any combination of the two. From this perspective, his five epoch-making papers of 1905 may be divided into three categories. The first two categories concern extensions and modifications of the two physical theories that dominated physics at the end of the nineteenth century: classical mechanics and Maxwell's electrodynamics.

1. His two papers on molecular dimensions and Brownian motion, papers 1 and 2 in this volume, are efforts to extend and perfect the classical-mechanical approach, especially its kinetic-molecular implications.
2. His two papers on the theory of special relativity, papers 3 and 4, are efforts to extend and perfect Maxwell's theory by modifying the foundations of classical mechanics in order to remove the apparent contradiction between mechanics and electrodynamics.

   In these four papers, Einstein proved himself a master of what we today call classical physics, the inheritor and continuer of the tradition that started with Galileo Galilei and Newton and ended with Faraday, Maxwell, and Boltzmann, to name but a few of the most outstanding representatives of this tradition. Revolutionary as they then appeared to his

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contemporaries, the new insights into the nature of space, time, and motion necessary to develop the special theory of relativity are now seen as the climax and culmination of that classical tradition.

3. His work on the light quantum hypotheses, paper 5, is the only one that he himself regarded as truly radical. In the first letter cited on p. 5 above, he wrote that this paper "deals with radiation and the energetic properties of light and is very revolutionary."[13] In it, he demonstrated the limited ability of both classical mechanics and Maxwell's electromagnetic theory to explain the properties of electromagnetic radiation, and introduced the hypothesis that light has a granular structure in order to explain novel phenomena such as the photoelectric effect, which cannot be explained on the basis of classical physics. Here and subsequently, Einstein, master of the classical tradition, proved to be its most severe and consistent critic and a pioneer in the search to find a new unified foundation for all of physics.

IV

The papers are presented in this volume in the order suggested by the three categories mentioned above, roughly the order of their distance from classical physics; but the reader should feel no compulsion to read them in that order. A good case can be made for the chronological order, for jumping immediately to the papers on special relativity and quantum theory—or for simply dipping into the volume as one's interest or fancy dictates.

In the body of this volume, the reader will find detailed discussions of each of these five papers drawn from the thematic introductory essays in volume 2 of *The Collected*

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Papers of Albert Einstein. Here I shall give an overview of Einstein's work up to and including 1905 in each of the three categories.

1. Efforts to Extend and Perfect the Classical-Mechanical Tradition

As recently discovered letters show, by the turn of the century Einstein was already occupied with the problems that were to take him beyond classical physics. Yet all of his papers published before 1905 treat topics that fall within the framework of Newtonian mechanics and its applications to the kinetic-molecular theory of matter. In his first two papers, published in 1901 and 1902, Einstein attempted to explain several apparently quite different phenomena occurring in liquids and solutions on the basis of a single simple hypothesis about the nature of the central force between molecules, and how it varies with their chemical composition. Einstein hoped that his work might help to settle the status of a long-standing (and now discarded) conjecture about a common basis for molecular and gravitational forces—one indication of his strong ambition from the outset to contribute to the theoretical unification of all the apparently disparate phenomena of physics. In 1901 he wrote: "It is a wonderful feeling to realize the unity of a complex of phenomena which, to immediate sensory perception, appear to be totally separate things."[14] Much later, looking back over his life, he wrote: "The real goal of my research has always been the simplification and unification of the system of theoretical physics."[15]

As mentioned on p. 12, another great project of nineteenth-century physics was the attempt to show that the

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empirically well-verified laws of thermodynamics could be explained theoretically on the basis of an atomistic model of matter. Maxwell and Boltzmann were pioneers in this effort, and Einstein saw himself as continuing and perfecting their work.

Einstein made extensive use of thermodynamical arguments in his first two papers; indeed, thermodynamics plays an important role in all of his early work. The second paper raises a question about the relation between the thermodynamic and kinetic-molecular approaches to thermal phenomena that he answered in his next paper. This is the first of three, published between 1902 and 1904, devoted to the atomistic foundations of thermodynamics. His aim was to formulate the minimal atomistic assumptions about a mechanical system needed to derive the basic concepts and principles of thermodynamics. Presumably because he derived it from such general assumptions, he regarded the second law of thermodynamics as a "necessary consequence of the mechanical worldview."[16] He also derived an equation for the mean square energy fluctuations of a system in thermal equilibrium. In spite of its mechanical origins, this formula involves only thermodynamical quantities, and Einstein boldly proceeded to apply the equation to an apparently nonmechanical system: black-body radiation (his first mention of it in print), that is, electromagnetic radiation in thermal equilibrium with matter. Black-body radiation was the only system for which it was clear to him that energy fluctuations should be physically significant on an observable length scale, and his calculations proved consistent with the known properties of that radiation. This calculation suggests that Einstein may already have had in mind an attempt to treat black-body radiation as if it were a mechanical

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system—the basis of his "very revolutionary" light quantum hypothesis of 1905.

In paper 1 of this volume, his doctoral dissertation, Einstein used methods based on classical hydrodynamics and diffusion theory to show that measurement of a fluid's viscosity with and without the presence of a dissolved substance can be used to obtain an estimate of Avogadro's number (see p. 12) and the size of the molecules of the dissolved substance. Paper 2, the so-called Brownian-motion paper, also extends the scope of applicability of classical mechanical concepts. Einstein noted that, if the kinetic-molecular theory of heat is correct, the laws of thermodynamics cannot be universally valid, since fluctuations must give rise to microscopic but visible violations of the second law when one considers particles sufficiently large for their motion to be observable in a microscope if suspended in a liquid. Indeed, as Einstein showed, such fluctuations explain the well-known Brownian motion of microscopic particles suspended in a liquid. He regarded his work as establishing the limits of validity within which thermodynamics could be applied with complete confidence.

2. *Efforts to Extend and Perfect Maxwell's Electrodynamics and Modify Classical Mechanics to Cohere with It*

Well before 1905, Einstein apparently was aware of a number of experiments suggesting that the mechanical principle of relativity—the equivalence of all inertial frames of reference for the description of any mechanical phenomena—should be extended from mechanical to optical and electromagnetic phenomena. However, such an extension was in

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conflict with what he regarded as the best current electrodynamical theory, Lorentz's electron theory, which grants a privileged status to one inertial frame: the ether rest frame (see p. 11).

In papers 3 and 4 in this volume, Einstein succeeded in resolving this conflict through a critical analysis of the kinematical foundations of physics, the theory of space and time, which underlies mechanics, electrodynamics, and indeed (although no others were known at the time) any other dynamical theory. After a profound critical study of the concept of simultaneity of distant events, Einstein realized that the principle of relativity could be made compatible with Maxwell's equations if one abandoned Newtonian absolute time in favor of a new absolute: the speed of light, the same in all inertial frames. As a consequence, the Newtonian-Galileian laws of transformation between the space and time coordinates of different inertial frames must be replaced by a set of transformations, now called the Lorentz transformations.[17] Since these transformations are kinematical in nature, any acceptable physical theory must be invariant under the group of such transformations. Maxwell's equations, suitably reinterpreted after eliminating the concept of the ether, meet this requirement; but Newton's equations of motion needed revision.

Einstein's work on the theory of relativity provides an example of his ability to move forward amid paradox and contradiction. He employs one theory—Maxwell's electrodynamics—to find the limits of validity of another—Newtonian mechanics—even though he was already aware of the limited validity of the former (see pp. 20–22 below).

One of the major accomplishments of Einstein's approach, which his contemporaries found difficult to apprehend, is

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that relativistic kinematics is independent of the theories that impelled its formulation. He had not only formulated a coherent kinematical basis for both mechanics and electrodynamics, but (leaving aside the problem of gravitation) for any new physical concepts that might be introduced. Indeed, developments in physics over almost a century have not shaken these kinematical foundations. To use terms that he employed later, Einstein had created a theory of principle, rather than a constructive theory.[18] At the time he expressed the distinction in these words: "One is in no way dealing here . . . with a 'system' in which the individual laws would implicitly be contained and could be found merely by deduction therefrom, but only with a principle that (in a way similar to the second law of thermodynamics) permits the reduction of certain laws to others."[19] The principles of such a theory, of which thermodynamics is his prime example, are generalizations drawn from a large amount of empirical data that they summarize and generalize without purporting to explain. In contrast, constructive theories, such as the kinetic theory of gases, do purport to explain certain phenomena on the basis of hypothetical entities, such as atoms in motion, introduced precisely to provide such explanations.

It is well known that important elements of Einstein's distinction between principle and constructive theories are found in Poincaré's writings. Two lesser-known sources that may have influenced Einstein's emphasis on the role of principles in physics are the writings of Julius Violle and Alfred Kleiner, which he is also known to have read.

In spite of the merits of the theory of relativity, however, Einstein felt that it was no substitute for a constructive theory: "A physical theory can be satisfactory only if its structures are composed of elementary foundations. The theory

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of relativity is just as little ultimately satisfactory as, for example, classical thermodynamics was before Boltzmann had interpreted the entropy as probability."[20]

3. Demonstrations of the Limited Validity of Both Classical Mechanics and Maxwell's Electromagnetic Theory, and Attempts to Comprehend Phenomena That Cannot Be Explained by These Theories

Einstein's efforts to perfect classical mechanics and Maxwell's electrodynamics, and to make both theories compatible, may still be regarded as extensions, in the broadest sense, of the classical approach to physics. However original his contributions in these areas may have been, however revolutionary his conclusions about space and time appeared to his contemporaries, however fruitful his work proved to be for the exploration of new areas of physics, he was still engaged in drawing the ultimate consequences from conceptual structures that were well established by the end of the nineteenth century. What is unique about his stance during the first decade of this century is his unwavering conviction that classical mechanical concepts and those of Maxwell's electrodynamics—as well as any mere modification or supplementation of the two—are incapable of explaining a growing list of newly discovered phenomena involving the behavior and interactions of matter and radiation. Einstein constantly reminded his colleagues of the need to introduce radically new concepts to explain the structure of both matter and radiation. He himself introduced some of these new concepts, notably the light quantum hypothesis, although he remained unable to integrate them into a coherent physical theory.

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Paper 5, Einstein's first paper on the quantum hypothesis, is a striking example of his style, mingling critique of old concepts with the search for new ones. It opens by demonstrating that the equipartition theorem,[21] together with Maxwell's equations, leads to a definite formula for the black-body radiation spectrum, now known as the Rayleigh-Jeans distribution. This distribution, which at low frequencies matches the empirically validated Planck distribution, cannot possibly hold at high frequencies, since it implies a divergent total energy. (He soon gave a similar demonstration, also based on the equipartition theorem, that classical mechanics cannot explain the thermal or optical properties of a solid, modeled as a lattice of atomic or ionic oscillators.)

Einstein next investigated this high-frequency region, where the classically derived distribution breaks down most dramatically. In this region, called the Wien limit, he showed that the entropy of monochromatic radiation with a fixed temperature depends on its volume in exactly the same way as does the entropy of an ordinary gas composed of statistically independent particles. In short, monochromatic radiation in the Wien limit behaves thermodynamically as if it were composed of statistically independent quanta of energy. To obtain this result, Einstein had to assume each quantum has an energy proportional to its frequency. Emboldened by this result, he took the final step, proposing his "very revolutionary" hypothesis that matter and radiation can interact only through the exchange of such energy quanta. He demonstrated that this hypothesis explains a number of apparently disparate phenomena, notably the photoelectric effect; it was this work that was cited by the Nobel Prize committee in 1921.

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In 1905 Einstein did not use Planck's full distribution law. The following year he showed that Planck's derivation of this law implicitly depends on the assumption that the energy of charged oscillators can only be an integral multiple of the quantum of energy, and hence these oscillators can only exchange energy with the radiation field by means of such quanta. In 1907, Einstein argued that uncharged oscillators should be similarly quantized, thereby explaining both the success of the DuLong-Petit law for most solids at ordinary temperatures and the anomalously low values of the specific heats of certain substances. He related the temperature at which departures from the DuLong-Petit law (see p. 175) become significant—now called the Einstein temperature—to the fundamental frequency of the atomic oscillators, and hence to the optical absorption spectrum of a solid.

In spite of his conviction of its fundamental inadequacy, Einstein continued to utilize still-reliable aspects of classical mechanics with remarkable skill to explore the structure of electromagnetic radiation. In 1909 he applied his theory of Brownian motion to a two-sided mirror immersed in thermal radiation. He showed that the mirror would be unable to carry out such a Brownian motion indefinitely if the fluctuations of the radiation pressure on its surfaces were due solely to the effects of random waves, as predicted by Maxwell's theory. Only the existence of an additional term, corresponding to pressure fluctuations due to the impact of random particles on the mirror, guarantees its continued Brownian motion. Einstein showed that both wave and particle energy fluctuation terms are consequences of Planck's distribution law for black-body radiation. He regarded this result as his strongest argument for ascribing physical reality to light quanta.

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Einstein was far from considering his work on the quantum hypothesis as constituting a satisfactory theory of radiation or matter. As noted on p. 19, he emphasized that a physical theory is satisfactory only "if its structures are composed of *elementary* foundations," adding "that we are still far from having satisfactory elementary foundations for electrical and mechanical processes."[22] Einstein felt that he had not achieved a real understanding of quantum phenomena because (in contrast to his satisfactory interpretation of Boltzmann's constant as setting the scale of statistical fluctuations) he had been unable to interpret Planck's constant "in an intuitive way."[23] The quantum of electric charge also remained "a stranger" to theory.[24] He was convinced that a satisfactory theory of matter and radiation must construct these quanta of electricity and of radiation, not simply postulate them.

As a theory of principle (see above), the theory of relativity provides important guidelines in the search for such a satisfactory theory. Einstein anticipated the ultimate construction of "a complete worldview that is in accord with the principle of relativity."[25] In the meantime, the theory offered clues to the construction of such a worldview. One clue concerns the structure of electromagnetic radiation. Not only is the theory compatible with an emission theory of radiation, since it implies that the velocity of light is always the same relative to its source; the theory also requires that radiation transfer mass between an emitter and an absorber, reinforcing Einstein's light quantum hypothesis that radiation manifests a particulate structure under certain circumstances. He maintained that "the next phase in the development of theoretical physics will bring us a theory of light, which may be regarded as a sort of fusion of the undulatory and emission

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theories of light."[26] Other principles that Einstein regarded as reliable guides in the search for an understanding of quantum phenomena are conservation of energy and Boltzmann's principle.

Einstein anticipated that "the same theoretical modification that leads to the elementary quantum [of charge] will also lead to the quantum structure of radiation as a consequence."[27] In 1909 he made his first attempt to find a field theory that would explain both the structure of matter (the electron) and of radiation (the light quantum). After investigating relativistically invariant, non-linear generalizations of Maxwell's equations, he wrote: "I have not succeeded . . . in finding a system of equations that I could see was suited to the construction of the elementary quantum of electricity and the light quantum. The manifold of possibilities does not seem to be so large, however, that one need draw back in fright from the task."[28] This attempt may be regarded as the forerunner of his later, almost forty-year-long search for a unified field theory of electromagnetism, gravitation, and matter.

In 1907, Einstein's attempt to incorporate gravitation into the theory of relativity led him to recognize a new formal principle, the principle of equivalence, which he interpreted as demonstrating the need to generalize the relativity principle (which he now began to call the *special* relativity principle) if gravitation is to be included in its scope. He found that, when gravitational effects are taken into account, it is impossible to maintain the privileged role that inertial frames of reference and Lorentz transformations play in the original relativity theory. He started the search for a group of transformations wider than the Lorentz group, under which the laws of physics remain invariant when gravitation is taken

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into account. This search, which lasted until the end of 1915, culminated in what Einstein considered his greatest scientific achievement: the general theory of relativity—but that is another story, which I cannot tell here.

Nor can I do more than allude to the many ways in which Einstein's work on the special theory of relativity and the quantum theory have inspired and guided not only many of the revolutionary transformations of our picture of the physical world during the twentieth century, but—through their influence on technological development—have contributed to equally revolutionary transformations in our way of life. One cannot mention quantum optics or quantum field theory, to name only a couple of theoretical advances; nor masers and lasers, klystrons and synchrotrons—nor atomic and hydrogen bombs, to name only a few of the multitude of inventions that have changed our world for good or ill, without invoking the heritage of Einstein's miraculous year.

EDITORIAL NOTES

[1]The phrase *anni mirabiles* (years of wonders) has been applied with more accuracy to the years 1664–1666 by Newton's biographer Richard Westfall in *Never at Rest/A Biography of Isaac Newton* (Cambridge, U.K.: Cambridge University Press, 1980; paperback edition, 1983), p. 140. This book may be consulted for generally reliable biographical information about Newton's life.

[2]I. Bernard Cohen, *Introduction to Newton's 'Principia'* (Cambridge, Mass.: Harvard University Press, 1971), p. 291.

[3]See, for example, Albrecht Fölsing, *Albert Einstein/A Biography*, tr. by Ewald Osers (New York: Viking, 1997), p. 121: "Never before and never since has a single person enriched science by so much in such a short time as Einstein did in his *annus mirabilis*." This book may be consulted for generally reliable biographical information about Einstein, but its scientific explanations should be treated with caution. For an account of Einstein's scientific work organized biographically, see Abraham Pais,

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'Subtle is the Lord . . . ': The Science and the Life of Albert Einstein (Oxford: Clarendon Press; New York: Oxford University Press, 1982).

[4]Einstein to Conrad Habicht, 18 or 25 May 1905, *The Collected Papers of Albert Einstein* (Princeton, N.J.: Princeton University Press, 1987–), cited hereafter as *Collected Papers*, vol. 5 (1993), doc. 27, p. 31. Translation from Anna Beck, tr., *The Collected Papers of Albert Einstein: English Translation* (Princeton University Press, 1987–), cited hereafter as *English Translation*, vol. 5 (1995), p. 20; translation modified.

[5]Einstein to Conrad Habicht, 30 June–22 September 1905, *Collected Papers*, vol. 5, doc. 28, p. 33; *English Translation*, p. 21; translation modified. Forty years later, when the explosion of the first atomic bombs brought the equivalence between mass and energy forcefully to the world's attention, Einstein might have wondered just what sort of trick the Lord had played on him.

[6]Westfall, *Never at Rest*, p. 140.

[7]Ibid., p. 205.

[8]Ibid., pp. 100, 137.

[9]Albert Einstein, *Autobiographical Notes*, Paul Arthur Schilpp, ed. and trans. (LaSalle, Ill.: Open Court, 1979), p. 15.

[10]Westfall, *Never at Rest*, p. 174.

[11]"Newton and the Law of Gravitation," *Arch. Hist. Exact Sci.* 2 (1965): 365–386, reprinted in Robert S. Cohen and John J. Stachel, eds., *Selected Papers of Leon Rosenfeld* (Dordrecht/Boston: Reidel, 1979), p. 65.

[12]Citation from Westfall, *Never at Rest*, p. 146.

[13]Einstein to Conrad Habicht, May 1905, *Collected Papers*, vol. 5, doc. 27, p. 31.

[14]Einstein to Marcel Grossmann, 14 April 1901, *Collected Papers*, vol. 1, doc. 100, p. 290.

[15]From the response to a questionnaire submitted to Einstein in 1932. See Helen Dukas and Banesh Hoffmann, *Albert Einstein: The Human Side* (Princeton, N.J.: Princeton University Press, 1979), p. 11 for the English translation, p. 122 for the German text.

[16]Einstein, "Kinetic Theory of Thermal Equilibrium and of the Second Law of Thermodynamics," in *Collected Papers*, vol. 2, doc. 3, p. 72 (p. 432 of the 1902 original).

[17]Lorentz had introduced such a set of transformations, and Henri Poincaré had so named them; but the kinematical interpretation that Einstein gave to them is quite different.

[18]For the distinction between theories of principle and constructive theories, see Albert Einstein, "Time, Space and Gravitation," *The Times* (London), 28 November 1919, p. 13; reprinted as "What Is the Theory of

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Relativity?" in *Ideas and Opinions* (New York: Crown, 1954), pp. 227–232. He later reminisced about the origins of the theory: "Gradually I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. The longer and the more desperately I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results. The example I saw before me was thermodynamics" (*Autobiographical Notes*, p. 48; translation, p. 49). For several years after 1905, Einstein referred to the "relativity principle" rather than to the "theory of relativity."

[19]Einstein, "Comments on the Note of Mr. Paul Ehrenfest: 'The Translatory Motion of Deformable Electrons and the Area Law,' " in *Collected Papers*, vol. 2, doc. 44, p. 411 (p. 207 of the 1907 original).

[20]Einstein to Arnold Sommerfeld, 14 January 1908, *Collected Papers*, vol. 5, doc. 73, pp. 86–88. A decade later, Einstein elaborated this idea: "When we say that we have succeeded in understanding a group of natural processes, we always mean by this that a constructive theory has been found, which embraces the processes in question" (from "Time, Space and Gravitation").

[21]This is a result of classical statistical mechanics, according to which each degree of freedom of a mechanical system in thermal equilibrium receives, on the average, the same share of the total energy of the system.

[22]Einstein to Arnold Sommerfeld, 14 January 1908, *Collected Papers*, vol. 5, doc. 73, p. 87.

[23]Ibid.

[24]See Einstein, "On the Present Status of the Radiation Problem," in *Collected Papers*, vol. 2, doc. 56, p. 549 (p. 192 of the 1909 original).

[25]Einstein, "On the Inertia of Energy Required by the Relativity Principle," in *Collected Papers*, vol. 2, doc. 45, pp. 414–415 (p. 372 of the 1907 original).

[26]Einstein, "On the Development of Our Views Concerning the Nature and Constitution of Radiation," in *Collected Papers*, vol. 2, doc. 60, pp. 564–565 (pp. 482–483 of the 1909 original).

[27]Einstein, "On the Present Status of the Radiation Problem," in *Collected Papers*, vol. 2, doc. 56, pp. 549–550 (pp. 192–193 of the 1909 original).

[28]Ibid., p. 550 (p. 193 of the 1909 original). This attempt at a field theory seems to represent Einstein's first step toward a field ontology.

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