Max Planck's Philosophy of Nature and His Elaboration of the Special Theory of Relativity

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1. INTRODUCTION

For more than three years after the publication of Einstein's first paper on the theory of special relativity Max Planck was nearly the only physicist of importance who received the new theory with the attention it deserved[1] and who immediately and without regard for the generally hesitant response to it by his colleagues applied himself to the exacting task of its elaboration. Almost all of his original contributions to the theory of special relativity appeared during this brief period. Planck defended the theory although it did not yet agree with experimental results, he encouraged his students to examine applications of the theory to a wide range of physical processes, and he wrote several papers in which he brilliantly demonstrated the heuristic power of the theory.

Planck, then in his late forties, received the theory of special relativity with a youthful—if critical—open-mindedness that he did not have for all of Einstein's new ideas. It is well-known, for example, that he long remained skeptical of Einstein's theory of the photoelectric effect.[2] His receptiveness for special relativity does not mark him as a revolutionary, however. In the present study I shall show that Planck's reaction and early contributions to the theory of special relativity were entirely in keeping with his conservatism, with his views of the nature of physical reality, and with his chief goal in physical research, namely, to uncover and confirm the absolutes of physics.

Planck frequently stated in public his metaphysical, epistemological, and ethical views. However, almost all of the addresses and

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[1] M. Planck, *Wissenschaftliche Selbstbiographie* (Leipzig, 1948), p. 31. The essay has been translated as M. Planck, *Scientific Autobiography and Other Papers,* trans. Frank Gegnor (New York, 1949).

[2] Cf. M. J. Klein, "Einstein and the Wave Particle Duality," *The Natural Philosopher, 3* (1964), 1–50.

essays containing them were written after 1908, that is, they were not published concurrently with his principal achievements in physics. The historian interested in the relationship between Planck's work in physics—in the present instance, in his work on special relativity—and his philosophical outlook is therefore forced to assume that Planck's philosophical views were essentially the same throughout his career. In the case of Planck's elaboration of the theory of special relativity, this assumption of continuity in Planck's philosophical thought allows us to assert a close correlation between the philosophical views Planck held at the time of publication of Einstein's theory and the nature of Planck's response to special relativity. In the present study I bring together and discuss in detail the elements needed to demonstrate such a correlation: a full account of the physical researches resulting from Planck's interest in the new theory, followed by an examination of the philosophical beliefs that motivated his involvement in its development.

2. PLANCK'S ELABORATION OF THE THEORY OF SPECIAL RELATIVITY

The Early Response to Einstein's Theory

Einstein submitted his first paper on relativity to the *Annalen der Physik* at the end of June 1905; it was published in September.[3] Max Planck and Wilhelm Wien were immediately impressed by Einstein's paper. Wien, the physicist Jakob J. Laub has pointed out, must be considered the "first of the great physicists" to appreciate the profundity and originality of Einstein's theory of special relativity. When Einstein's article appeared in the *Annalen,* Wien asked Laub, who was then studying under Wien at Würzburg, to prepare a colloquium talk on the subject,[4] but Wien did not support the

[3] A. Einstein, "Zur Elektrodynamik bewegter Körper," *Ann. d. Phys., 17* (1905), 891–921. The article has been translated a number of times; see A. Einstein, "On the Electrodynamics of Moving Bodies," in H. A. Lorentz et al., *The Principle of Relativity,* trans. W. Perrett and G. B. Jeffrey (New York, n.d.), pp. 35–65.

[4] J. J. Laub to C. Seelig, 11 September 1959. The letter is contained in the Seelig papers in the library of the Eidgenössischen Technischen Hochschule, Zurich, Switzerland, to whom I am indebted for permission to read and make use of the material; in particular I acknowledge the valuable help given to me by Dr. A. Jaeggli.

Very little attention has thus far been paid to Laub. He seems to have been theory and remained skeptical until 1909.[5] He was unable to accept the second postulate of the theory, the invariance of the velocity of light.[6] Planck has also been called "Einstein's earliest patron in scientific circles."[7] The first lecture Planck gave in the colloquium series at Berlin University in the fall of 1905 was a review of Einstein's relativity paper. Max von Laue, who was Planck's assistant in 1905, was so impressed by the lecture that he used his next vacation to visit Einstein in Berne.[8]

On the whole, however, the response to the new theory during the first three or four years after the publication of Einstein's paper was not very great.[9] Most of it came from physicists in Germany, Austria, and other German speaking countries and appeared in German language publications. Only a handful of physicists came to grips directly with the issues that Einstein had presented. Of these, Laub was the most penetrating and the most perceptive.[10] Max Abraham did not accept the theory, but he appreciated the logic of Einstein's arguments and the basic premises of the theory.[11] Hermann Minkowski, on the other hand, failed to appreciate the significance of Einstein's approach, even though he cast the theory of special relativity into a formalism of great heuristic power. His emphasis was on creating a theory of matter rather than a theory of

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particularly instrumental in convincing Wilhelm Wien of the meaning and power of Einstein's theory. The early relationship between Einstein and Laub is discussed in Carl Seelig, *Albert Einstein: Eine dokumentarische Biographie* (Zurich, 1952), pp. 85-87.

5W. Wien, *Über Elektronen* (Leipzig, 1906; 2nd ed. 1909).

6*Ibid.*, 2nd ed., p. 28. The second edition contains a number of new footnotes, one of which (note 2, p. 28) extends over nearly five pages and gives a brilliant account of the fundamental aspects of Einstein's theory of relativity, thereby rendering meaningless a good part of the text to which it refers.

7G. Holton, "Mach, Einstein, and the Search for Reality," *Daedalus, 97* (1968), 636-673; on p. 642.

8M. von Laue to C. Seelig, 13 March 1952. The letter is contained in the Seelig papers (note 4).

9S. Goldberg, *Early Response to Einstein's Theory of Relativity, 1905-1911: A Case Study in National Differences* (diss. Harvard University, 1969); "Poincaré's Silence and Einstein's Relativity," *Brit. J. Hist. Sci., 5* (1970), 73-84; "In Defense of Ether; The British Response to Einstein's Theory of Relativity, 1905-1911," *Hist. Studies Phys. Sci., 2* (1970), 89-125.

10See especially J. J. Laub, "Zur Optik der bewegten Körper," *Ann. d. Phys., 23* (1907), 738-744; *25* (1908), 175-184.

11S. Goldberg, "The Abraham Theory of the Electron: the Symbiosis between Theory and Experiment," *Arch. Hist. Exact Sci.,* 7 (1970), 9-25.

measurement.[12] H. A. Lorentz, by his own account, did not understand the difference between his own electron theory and Einstein's kinematical theory based on the behavior of rigid rods, perfect clocks, and light signals until after 1909.[13]

If physicists were reluctant to accept Einstein's theory, it was often because they did not grasp the significance of his approach, not because they were wary of the elements of the theory, which were known to them and had individually been discussed since 1902.[14] Laub was struck by his colleagues' inability to understand the logic of Einstein's theory;[15] Arnold Sommerfeld found it impossible to convince Wien of the second postulate.[16]

Some physicists were so convinced of the truth of existing theory that they rejected Einstein's theory outright. For example, in 1909 Fritz Hasenöhrl began a review article on the literature on the concept of the inertia of energy by stating that he would only discuss the development of the concept "from the standpoint of the true Lorentz theory."[17] Hasenöhrl accredited recent attention to Einstein's principle of relativity to "its blinding elegance."

The First Experimental Tests of Einstein's Theory

The first physicist to subject the predictions of the theory of special relativity to a comparison with experimental results was Walter

[12] Since Minkowski's untimely death cut off his important contributions, it is difficult to give a definitive judgment of it. His work was, in a sense, carried on by his last assistant, Max Born. In the years 1908–1910 Born published a series of papers which reveal a gradual transformation of his point of view; abandoning Minkowski's interpretation, he came to appreciate fully the kinematical character of Einstein's theory. See S. Goldberg, *Early Response . . . , op. cit.* (note 9), chap. 2.

[13] S. Goldberg, "The Lorentz Theory of the Electron and Einstein's Theory of Relativity," *Amer. J. Phys., 37* (1969), 982–994; G. Holton, "On the Origins of the Special Theory of Relativity," *Amer. J. Phys., 28* (1960), 627–636; H. A. Lorentz, *The Theory of Electrons* (New York, 1952), p. 321, fn. 72*. This book was originally published in 1909. The starred footnotes were added to the second edition, published in 1915.

[14] S. Goldberg, "Henri Poincaré and Einstein's Theory of Relativity," *Amer. J. Phys., 35* (1967), 934–944; G. Holton, *ibid.*

[15] J. J. Laub to C. Seelig, 11 September 1959 (note 4).

[16] A. Sommerfeld, "Ein Einwand gegen die Relativtheorie und seine Beseitigung," *Phys. Zs., 8* (1907), 841–842; see especially the discussion between Sommerfeld and Wien.

[17] F. Hasenöhrl, "Die Trägheit der Energie," *Jahrb. Rad. u. Elek., 6* (1909), 485–502; esp. pp. 485–486.

Kaufmann.[18] Late in 1905 Kaufmann completed a series of experiments on the changes in the "transverse" mass of an accelerating electron, that is, on the changes in the mass of an electron when the electron is accelerated in a direction perpendicular to the direction of motion. Kaufmann had carried out his investigation by photographically determining the magnetic and electric deflections of β-rays emitted by a kernel of radium bromide. He had obtained photographed deflection curves each point of which corresponded to a different velocity and mass of the electron. Kaufmann, who had been making measurements of this kind since 1901, now used his experimental technique to test the validity of the various electron theories, that is, Abraham's theory of the rigid electron, Bucherer's theory of the deformable electron of constant volume, Lorentz' theory of the deformable electron of variable volume, and Einstein's theory relating changes in the specific charge of the electron to the problem of simultaneity. If he could determine the velocity that corresponded to any point of the photographed curves from the constants of his experimental setup, then, Kaufmann reasoned, a comparison between this value and any of the velocities derived from the curve by applying one or the other of the three theories would show which, if any, of the theories agreed best with experience. More importantly, if the measurements confirmed the validity of Lorentz' and Einstein's theories—their predictions were the same[19]—then one would have to assume an "internal potential energy" of the electron to account for the work required in the deformation of Lorentz' electron, and it would be proven that a purely electromagnetic foundation of the mechanics of the electron as well as of mechanics in general is impossible.[20]

Planck took up the defense of the theory of special relativity in 1906. In March of 1906 Planck read a paper before the German Physical Society in which he investigated the theoretical implications

[18] W. Kaufmann, "Über die Konstitution des Elektrons," *Ann. d. Phys., 19* (1906), 487-553.

[19] S. Goldberg, *op. cit.* (note 11). In fact, Einstein's first prediction for the transverse mass of the electron differed formally from Lorentz' prediction due to Einstein's idiosyncratic definition of force in his first paper on relativity. Lorentz' expression, as almost everyone immediately recognized, was implied by Einstein's. Cf. A. I. Miller, "On Lorentz' Methodology," *Brit. J. Phil. Sci., 25* (1974), 29-45, esp. p. 42.

[20] W. Kaufmann, *op. cit.* (note 18), p. 494.

of Einstein's work.[21] In September, at the Stuttgart meeting of the Society of German Natural Scientists and Physicians, he presented the results of his examination of Kaufmann's experimental techniques and analysis, for Kaufmann had concluded in favor of Abraham's and Bucherer's theories and against Lorentz' and Einstein's, particularly against the admissibility of the relativity principle.[22]

Planck took up work on the theory of special relativity not because he was convinced that it was correct, but because he believed that a physical idea of such simplicity and generality deserved to be investigated in more than one way. His first theoretical task was to find the equations of motion that would have to replace Newton's if the principle of relativity was to be generally valid. Planck applied the Lorentz transformations, Newton's second law, and the transformation equations for electric and magnetic field strength as given by Einstein in his first 1905 paper on relativity to a mass point having a charge e and derived the equations of motion for the particle that are valid for any inertial frame of reference under the influence of an electromagnetic field. By comparing these equations with the Lagrangian equation of motion, he then derived the kinetic potential and, by another simple step, the kinetic energy of the mass point. Finally Planck derived the least action formulation and Hamilton's canonical equations. He concluded that all of these relations also apply to any other coordinate system related by the Lorentz transformations.[23] Planck's paper was important because it

[21] M. Planck, "Das Prinzip der Relativität und die Grundgleichungen der Mechanik," *Verh. d. Deutsch. Phys. Ges., 8* (1906), 136–141.

[22] M. Planck, "Die Kaufmannschen Messungen der Ablenkbarkeit der β-Strahlen in ihrer Bedeutung für die Dynamik der Elektronen," *Phys. Zs.*, 7 (1906), 753–761; *Verh. d. Deutsch. Phys. Ges., 8* (1906), 418–432.

[23] In 1905, H. Poincaré had already considered many of the problems taken up by Planck in this paper. He had, among other things, correctly formulated the transformation equations for force and had considered the least action formulation for the electromagnetic Lagrangian. Planck's approach and point of view had little in common with Poincaré's. Planck began from the principle of relativity and the Lorentz transformations and deduced the consequences. Poincaré, on the other hand, used the Lorentz transformations to explain why it was not possible to detect absolute motion. H. Poincaré, "Sur la dynamique de l'électron," *Rend. Cir. mat. di Palermo, 21* (1906), 129–176. Cf. H. Poincaré, *Oeuvres d'Henri Poincaré* (Paris, 1934–1954), *9,* 494–550. See H. M. Schwartz, "Poincaré's Rendiconti Paper on Relativity," *Amer. J. Phys., 39* (1972), 1287–1294; *40* (1973), 862–872, 1282–1287. Schwartz has modern-

showed that one could use the principle of relativity to express the laws of motion in closed form and that one did not need quasi-stationary approximations such as the one Abraham had been forced to use because of his strict adherence to an electromagnetic worldview.[24]

Planck's first purpose in examining Kaufmann's work was to find out how great a distance there is between the individual measured deflection and the corresponding deflections calculated according to the different theories with the constants of the experimental setup.[25] He chose not to assume—as Kaufmann had—that the observed deflections are at once reducible to infinitely small deflections and, hence, that the simultaneous electric and magnetic deflections are independent of one another.[26] In spite of his different method of calculation, Planck found that his results agreed with Kaufmann's. Nonetheless, he insisted that the results of the experiment do not justify Kaufmann's conclusion. He pointed out that the deflections predicted by the theories are closer to each other than the prediction of any one theory to the observed deflection. Dismissing as inconclusive whatever objections might be made to Kaufmann's work, Planck saw no alternative but to assume that there was still a "significant gap" in the theoretical interpretation of the measured quantities which would have to be filled before Kaufmann's measurements could be used to decide between Abraham's theory and the relativity theory.[27]

In the ensuing discussion Kaufmann, Abraham, and Bucherer pressed Planck to decide for one of the theories on the basis of Kaufmann's experiments, but Planck refused. Abraham then fell back on theoretical arguments. He insisted that his theory is correct because it is the only one of the theories that has been built on a purely electromagnetic basis. That, he said, is more convincing than the experiments. Lorentz' theory requires nonelectromagnetic forces to ensure the stability of the electron and Einstein's theory says

ized all notation and draws conclusions that do not flow from a historical study of the context of Poincaré's paper. See also A. I. Miller, "A Study of Henri Poincaré's "Sur la Dynamique de l'Electron'," *Arch. Hist. Exact Sci., 10* (1974), 207-328.

24 S. Goldberg, *op. cit.* (note 11).

25 M. Planck, *op. cit.* (note 22), p. 419.

26 W. Kaufmann, *op. cit.* (note 18), p. 524.

27 M. Planck, *op. cit.* (note 22), p. 428.

nothing about the electromagnetic nature of the electron. In reply, Planck pointed out that the electromagnetic basis of Abraham's theory is as much a postulate as the postulate of the impossibility of detecting absolute motion of the Lorentz and the Einstein theories. Planck added that he preferred the relativity postulate.[28]

Within six months of the Stuttgart meeting A. Bestelmeyer established a new value for the rest mass of the electron.[29] Bestelmeyer had used electrons produced by X-rays of various intensities to determine to what extent the ratio of charge to mass might be a function of the intensity of the primary radiation. Rather than using parallel electric and magnetic fields to deflect the charged particles as Kaufmann had done, Bestelmeyer introduced the now familiar crossed field velocity filter arrangement. Bestelmeyer's new value for the specific charge of the resting electron was approximately nine percent lower than Kaufmann's; used in conjunction with Kaufmann's data and Kaufmann's method of analysis, the new value led to results that were so close to the predictions of both Abraham's theory and Lorentz' and Einstein's theories that they could not be used to differentiate between the theories.

In the meantime others, chiefly H. Geiger in England and J. Stark in Germany, were investigating the ionization in gases caused by β-radiation. Planck had come to question the accuracy of the constants of Kaufmann's experimental setup since they yielded a velocity greater than that of light for the least deflection radiation. He now attributed part of the failure of Kaufmann's experiment to a miscalculation of the electric field.[30] He argued that, since the recent experiments have shown that β-radiation ionizes the air remaining between the condenser plates in Kaufmann's apparatus, the electric field between the plates can no longer be assumed to be homogeneous as Kaufmann had assumed. Planck repeated his and Kaufmann's calculations again, taking into account the changed view of the electric field and Bestelmeyer's new value. This time, although his result still did not clearly confirm either Abraham's or the relativity theory, Planck concluded that it "increased the chances" of the latter. Kaufmann denied that his experimental results could be so

[28] M. Planck, *op. cit.* (note 22), pp. 759–761.

[29] A. Bestelmeyer, "Spezifische Ladung und Geschwindigkeit der durch Röntgenstrahlen erzeugten Kathodenstraheln," *Ann. d. Phys., 22* (1907), 429–447.

[30] M. Planck, "Nachtrag zur Besprechung der Kaufmannschen Ablenkungsmessungen," *Verh. d. Deutsch. Phys. Ges., 9* (1907), 301–305.

grossly in error and continued to dispute the question with Planck and Stark through the year 1907.[31] Eventually, however, his contributions in this area stopped.

During all of this time Einstein refrained from entering the dispute, but he remarked that even though Kaufmann's data seemed to favor the predictions of the Abraham theory, his theory was the only one that comprehended a wide variety of phenomena.[32]

Thermodynamic Theories of Stationary Radiation in Moving Blackbodies

In 1904 Fritz Hasenöhrl had taken up the problem of bringing the laws governing stationary radiation in moving bodies into agreement with thermodynamics.[33] Hasenöhrl had arrived at results that contradicted the second law of thermodynamics and he had chosen to correct the situation by adopting the Lorentz contraction hypothesis. The following year Kurd von Mosengeil had investigated the same problem at Planck's suggestion and concluded that Hasenöhrl had based his work on an incorrect argument and that a correctly constructed theory of stationary radiation in moving blackbodies did not need the contraction hypothesis. When Mosengeil died early in 1906 before the publication of his paper in the *Annalen der Physik*, Planck edited his student's work and saw it through publication.[34]

[31] *Ibid.;* W. Kaufmann, "Bemerkungen zu Herrn Planck: Nachtrag zur Besprechung der Kaufmannschen Ablenkungsmessungen," *Verh. d. Deutsch. Phys. Ges., 9* (1907), 667–673; J. Stark, "Bemerkung zu Herrn Kaufmann's Antwort auf einen Einwand von Herrn Planck," *Verh. Deutsch. Phys. Ges., 10* (1908), 14–16. W. Kaufmann, "Erwiderung an Herrn Stark," *Verh. d. Deutsch. Phys. Ges., 10* (1908), 91–95.

[32] A. Einstein to J. Stark, 1 November 1907. Einstein thanked Stark for pointing out to him Planck's work on Kaufmann's experiments. He wrote that he had known nothing of Planck's research: "Es ist gut, dass Sie mich auf die Planck'sche Arbeit über die Kaufmann'schen Versuche aufmerksam gemacht haben. Ich wusste nichts von einer Untersuchung des Herrn Planck über diesen Gegenstand." I am indebted to the Handschriftenabteilung, Staatsbibliothek, Preussischer Kulturbesitz, Berlin (Dahlem), for permission to quote the letter from Einstein to Stark. The letter is contained in the collection Nachlass Stark and is designated Autogr. 1/223. Cf. G. Holton, *op. cit.* (note 7), pp. 651–652.

[33] F. Hasenöhrl, "Zur Theorie der Strahlung in bewegten Körpern," *Ann. d. Phys., 15* (1904), 344–370; "Ueber die Veränderung der Dimensionen der Materie infolge ihrer Bewegung durch den Aether," *Sitzungsber. Akad. Wiss. Wien, 113* (1904), 469–492.

[34] Kurd von Mosengeil, "Theorie der stationären Strahlung in einem gleichförmig bewegten Hohlraum," *Ann. d. Phys., 22* (1907), 867–904. An

It is instructive to consider Hasenöhrl's and Mosengeil's work in some detail in the present study. Like Planck, Hasenöhrl and Mosengeil tried to construct theories that would answer the questions raised by recent work in the area of heat radiation. Unlike Planck, however, they sought their answers only in the careful examination and combination of accepted theories and concepts. Other physicists, Hasenöhrl noted, had attempted to develop a theory of heat radiation in moving bodies from the point of view of the electromagnetic theory. Hasenöhrl and Mosengeil used thermodynamic concepts instead, supplementing them by electromagnetic ones where necessary. As a consequence of their cautious adherence to proven modes of physical thought they obtained only specialized results. When Planck came to treat the same problem, he achieved through his emphasis on general principles—the principle of least action and the principle of relativity—a general new dynamics of moving systems, which included heat radiation theory only as a special case.

Until physicists began to study the problem of heat radiation in moving bodies, it had been possible for them to treat the energy of a body in such a way that the kinetic energy of the body was completely divorced from any consideration of the body's internal state. That separation ceased to be possible for moving, radiation-filled cavities; it was therefore necessary to account for the energy of such a body in a new way. Hasenöhrl chose a thermodynamic approach, even though he realized that the laws of thermodynamics were inadequate for his purpose.[35] Thermodynamics failed to provide a value for the radiation pressure on a moving surface and Hasenöhrl used the value that Abraham had derived from the Lorentz theory: the radiation pressure was equal to the ratio of the total relative radiation (to be defined below) to the velocity of light.

After giving a summary of the geometric relations between absolute and relative radiation velocity and direction, Hasenöhrl first defined the kinds of radiation, that is, "absolute radiation," "total relative radiation," and "true relative radiation." He defined absolute

earlier version of this work appeared with the subtitle *Berliner Inaugural-Dissertation* (Berlin, 1906). Since Planck made significant alterations in the article, the editors of Planck's collected papers included it in the collection. See M. Planck, *Physikalische Abhandlungen und Vorträge* (Braunschweig, 1958), henceforth referred to as *PAV*; in *2*, 138–175.

[35] F. Hasenöhrl, "Zur Theorie der Strahlung . . . ," *op. cit.* (note 33).

radiation as the quantity of energy crossing a unit surface at absolute rest in unit time, total relative radiation as the quantity of energy crossing a unit surface moving with absolute velocity v in unit time, and true relative radiation as the total relative radiation decreased or increased by the work done by the radiation pressure or against the radiation pressure, respectively. Hasenöhrl next calculated the radiation density in the moving cavity, one part of which is equivalent to the work required to put the system into motion. Poynting and others had stated that mechanical work is directly transformed into radiation energy and vice versa purely as a consequence of the energy law and independently of any special assumptions about the nature of radiant heat. Hasenöhrl applied this point of view to his investigation and showed that the changes in the radiation process due to the motion of the body are reversible. He identified the mechanical work as an apparent mass change due to the inertia of the radiation.

Hasenöhrl concluded his analysis by examining the effects on the temperature of a radiation-filled cavity of a closed cycle of velocity changes under adiabatic conditions. His calculations showed that at the end of the process the net work was zero and the energy density the same as at the beginning of the process, but that the temperature was higher, a result that contradicted the second law of thermodynamics. He considered two explanations. One would require the assumption that the emission capacity of a blackbody changes as a function of its velocity, that is, that the internal energy of a radiating body is a function of its motion. If this were so, he said, then his work, including his derivation of radiation pressure, would be wrong. The hypothesis did not appear probable to him, but he admitted that it was possible. The other possible explanation required the Lorentz-Fitzgerald hypothesis that the dimensions of matter depend on their absolute velocity.[36] The alteration in the energy density produced by the change in volume in this case was, according to Hasenöhrl's calculations, just sufficient to compensate for the change in temperature.

Mosengeil claimed that his analysis differed greatly from Hasen-

[36] Lorentz' 1904 paper "Electromagnetic Phenomena in a System Moving with any Velocity less than that of Light" [reprinted in H. A. Lorentz et al., *The Principle of Relativity* (New York, n.d.), pp. 9–34] in which he placed the Lorentz-Fitzgerald contraction into the framework of his transformation equations had not yet been published.

öhrl's.[37] He believed that Hasenöhrl attributed greatest significance to the apparent support for Lorentz' theory that had been the result of his investigation. Mosengeil could not accept Hasenöhrl's result, since he believed that Hasenöhrl had made an error in his analysis by using the Lambert cosine law to calculate the energy density in a moving blackbody. He wanted to show that an accurate theory of stationary radiation in blackbodies would have different results.

In the first part of his paper Mosengeil assumed a moving cavity and a resting observer. He first showed that the intensity of the stationary radiation in moving blackbodies is independent of the nature of the emitting substance. He then derived expressions for the pressure, entropy, energy, and momentum of radiation in a moving cavity in terms of the temperature, volume, and speed of the cavity. He did not need the Lorentz contraction hypothesis but was able to obtain the desired expressions by using the well-known relationship between energy and momentum of electromagnetic radiation, and by defining the necessary relationship between the temperatures of blackbodies at rest and in motion.[38] In the next part of the paper, Mosengeil again derived these results by now assuming an observer who is moving relative to a blackbody and by applying the Lorentz transformation equations. He concluded that one did not need the Lorentz contraction hypothesis to show that the laws of stationary radiation in moving blackbodies are compatible with both electrodynamics and thermodynamics. As far as the validity of the principle of relativity was concerned, that was still an "open question."[39]

Hasenöhrl found Mosengeil's analysis without error. However, he rejected Mosengeil's criticism by correctly pointing out that, if the Lambert relationship applied to systems at rest, then it should also apply to systems in motion, since, according to Lorentz, uniform motion should have no effect on the phenomena.[40] Later Hasenöhrl attributed the difference in their analyses to Mosengeil's assumption of a change in temperature in the cavity with changing velocity rather than to the use of the Lambert relationship. Hasenöhrl proved

[37] K. von Mosengeil, *op. cit.* (note 34), p. 867.

[38] *Ibid.*, pp. 871–895.

[39] *Ibid.*, p. 904.

[40] F. Hasenöhrl, "Zur Theorie der stationären Strahlung in einem gleichförmig bewegten Hohlraume," *Ann. d. Phys., 22* (1907), 791–792.

his point by deriving results identical with Mosengeil's with the Lambert relationship.[41]

Given the structure of Mosengeil's paper—the introduction criticizing Hasenöhrl's work, the examination of the laws governing radiation in blackbodies from the point of view of a moving blackbody and resting observer, and then a rederivation of the same results from the point of view of relative motion using the Lorentz transformations—Mosengeil's unwillingness to commit himself to the principle of relativity appears to be a nonsequitur. If we remember, however, that Mosengeil's paper was edited and corrected by Planck, then Mosengeil's remarks may be seen as the—reflected or direct—expression of Planck's wariness with regard to the validity of Einstein's theory which continued through 1908.

Dynamics of Moving Systems

Several months after the appearance of Mosengeil's work, Planck presented a paper before the Prussian Academy of Sciences in which he developed a general theory of dynamics. He included in it not only Mosengeil's study of the laws governing stationary radiation in moving cavities, but also his own earlier analysis of the dynamics of ponderable matter.[42] Planck believed that it had become necessary to reevaluate certain concepts and laws of theoretical physics that had long been taken for granted.

> Recent experimental as well as theoretical investigations in the area of heat radiation have led to the common result that any system that has been stripped of all ponderable matter and consists entirely of electromagnetic radiation obeys both the fundamental equations of mechanics and the two laws of thermodynamics so completely that, so far, none of the conclusions drawn from these laws have proven inadequate. As a consequence it has become necessary to revise the foundations of a number of conceptions and laws which up to now have commonly been used as basic fixed and almost self-evident prerequisites of all theoretical speculations

[41] F. Hasenöhrl, "Zur Thermodynamik bewegter Systeme," *Sitzungsber. Akad. Wiss., Wien, 116* (1907), 1391–1405; *117* (1908), 207–215.

[42] M. Planck, "Zur Dynamik bewegter Systeme," *Sitzungsber. Preuss. Akad. Wiss.* (1907), pp. 867–904; also in *Ann. d. Phys., 26* (1908), 1–34; and in *PAV, 2,* 176–209. All references are to the version that appeared in the *Annalen der Physik.*

> in these fields. A closer look at them shows that some of the simplest and most important among them in the future can no longer claim exact validity but are no more than widely applicable and, as far as applications are concerned, very important approximations.[43]

Planck discussed three of the fundamental concepts that needed to be examined. He first considered the accepted definition of energy. It was no longer permissible, he asserted, to define the energy of a moving body as the sum of kinetic and potential energy. Every ponderable body contains a finite quantity of energy in the form of radiant heat; when the body is set in motion, the radiant heat is also set in motion. Although the energy of this radiant heat is a function of the velocity, it is impossible in the case of radiant heat to separate the kinetic from the potential energy, and, therefore, it is impossible to divide the total energy of the body into kinetic and potential energy. Planck next showed that the concept of inertial mass of a ponderable body similarly needed to be redefined. From the time of Newton, he said, the concept of mass as an absolutely unchanging property of matter, independent of physical or chemical action, had been the first building block of almost every physical world system. It is easy to show, however, that the mass of a body is not constant but a function of the temperature of the body. It is most directly defined in terms of the kinetic energy, and since it is impossible to completely separate the energy of motion from the internal energy one may say that a constant with the properties of inertial mass in the classical sense does not exist. Attempts to distinguish between "true" and "apparent" mass and to assign to the first the properties of an absolute constant merely masked the problem, Planck believed, and did not solve it. If the "true" mass were taken to be an invariant, the concepts of momentum and kinetic energy would lose their usual meaning. Finally Planck considered the question of the identity of inertial and ponderable mass. The radiant energy in a totally evacuated space, bounded by mirrored walls, contains inertial mass. Planck found it necessary to ask whether or not radiant energy then also contains ponderable mass, for, if it does not, then the generally accepted hypothesis of the identity of inertial and ponderable mass no longer holds. In the face of this state of affairs Planck found it very important to seek out and emphasize

[43] *Ibid.*, p. 1.

those of the laws of general dynamics that had proven to be absolutely exact for the results of recent researches, too, and to distinguish them from those that were now found to be only useful approximations.

Of all the well-known laws Planck found only the principle of least action still generally valid: it embraced mechanics, electrodynamics, and the two laws of thermodynamics, as well as the laws of blackbody radiation, as Planck was about to show. But the principle of least action alone was not a sufficient basis for a general dynamics, since it did not contain a substitute for the division of energy into kinetic and potential energy. Hence Planck proposed combining the principle of least action with the principle of relativity and developing the consequences to which such a combination might lead, not only for ponderable bodies, but for cavity radiation as well.

As in his other discussions of the theory of relativity, Planck noted that there was as yet no direct confirmation of the theory of relativity except for the results of the Michelson-Morley experiment. But, he added, there was also nothing known to prevent one from ascribing general and absolute validity to the principle. Planck argued that the principle was so decisive and fruitful that it should be given as thorough an investigation as possible; the investigation he proposed was to take the form of an examination of the consequences of the principle.[44]

Planck began his analysis of the consequences of combining the principle of least action with the principle of relativity by discussing blackbody radiation in a vacuum, because blackbody radiation is the only physical system whose dynamic, electrodynamic, and mechanical properties can be stated with absolute precision and independently of conflicting special theories. He expressed the entropy, energy, pressure, and momentum of blackbody radiation as functions of the independent variables velocity, volume, and temperature, making use of Mosengeil's equations.

Planck next wrote general expressions for energy, momentum, and kinetic potential. He noted that the general equations also apply to blackbody radiation. Then, in accordance with his introductory remarks, he substituted the principle of relativity for the usual analysis of the kinetic potential. He applied the Lorentz transformations to his general equations and derived the relationships between the variables of a body in different reference systems. Planck concluded

[44] *Ibid.*, pp. 1–5.

the first part of his analysis by listing the many properties and relations that are invariant in a transformation from one reference system to another.[45]

In the last section of the paper Planck applied to specific cases the general dynamical relations he had derived. He pointed out that the most important consequence of these general relations involved the dependence of the physical state of a body on its velocity. The special relations resulting from this dependence could be summarized in a single differential equation that represented the general expression for the application of the relativity principle to the kinetic potential. Then he showed that for the case of blackbody radiation his general results reduced to the specific equations Mosengeil had derived. Next Planck redefined inertial mass. He showed that the most general expression for inertial mass was equivalent to the differential equation he had derived. It stated that "every increase or decrease of heat changes the inertial mass of a body in such a way that the increase of the mass is always equal to the quantity of heat that is absorbed during an isobaric change of the body divided by the square of the velocity of light in a vacuum."[46] H. E. Ives, an American physicist, later referred to Planck's result as the "first valid and authentic derivation" of the relationship between mass and energy.[47] Planck concluded from his theory that every body contains a colossal quantity of internally stored energy—Planck called it "latent" energy—which ordinary physical and chemical processes hardly affect. He added that to pursue the implications of this result one could no longer use the concepts of kinetic gas theory and treat the chemical atom as a rigid body or as a material point or consider inertial mass as something given, nor could one still assume equipartition of energy in statistical equilibrium. Planck suggested that the relationship between mass and energy might prove to be verifiable by experimental tests.

Shortly after Planck had published his paper, Hasenöhrl responded with a modification of his earlier work of 1904 and 1905 in which he derived essentially all of Planck's results by using the hypothesis that no experiment could reveal the difference between absolute rest and inertial motion. The use of this hypothesis required the

[45] *Ibid.*, p. 23.
[46] *Ibid.*, p. 29.
[47] *Ibid.*, p. 27. Cf. H. Ives, "Derivation of the Mass-Energy Relation," *J. Opt. Soc. Amer.*, *42* (1952), 540–543.

introduction of the Lorentz-Fitzgerald contraction. At the end of his analysis, Hasenöhrl, obviously puzzled and hurt, remarked that, although he had introduced the notion of temperature dependent mass among other things in his earlier work, Planck had not acknowledged his contributions.[48]

Planck had demonstrated the heuristicity of the theory of relativity, but he was well aware that the theory was not yet fully established. In a paper delivered at the 1908 meeting of the Society of German Scientists and Physicians at Cologne[49] he noted that Einstein's theory differed from other similarly applicable theories only with respect to very small terms, and that except for those terms it could be considered correct. In the same paper he continued to develop the theoretical consequences of the theory of relativity in connection with his constant and primary concern, the unification of the different fields of physics. His remarks dealt with the role of the principle of action and reaction in electrodynamics. Lorentz had denied the principle general validity in his electrodynamics. Max Abraham had contradicted Lorentz and maintained the validity of the principle provided that mechanical momentum be supplemented by electromagnetic momentum. Abraham had justified the new concept by establishing an analogy between the conservation of momentum and that of energy. Reluctant to accept a generalization of momentum that was based on an analogy between the universal physical concept of energy and the specifically mechanical concept of momentum, Planck proposed instead to derive a suitably generalized definition of momentum from general dynamics. He noted that a definition that united within itself the mechanical and electromagnetic form was possible if one assumed the validity of Einstein's theory of relativity.

In the theory of relativity momentum can be defined in terms of a vector representing energy flow. Specifically, Planck stated that the momentum per unit volume at a point in space is equal to the ratio of the energy flow per unit surface area per unit time (a vector) to the square of the speed of light. He found that this definition of momentum provided the desired new insight into the "real signifi-

[48] F. Hasenöhrl, "Zur Thermodynamik bewegter Systeme," *op. cit.* (note 41), esp. *117,* 215.

[49] M. Planck, "Bemerkungen zum Prinzip der Aktion und Reaktion der allgemeinen Dynamik," *Verh. Deutsch. Phys. Ges., 10* (1908), 728–732; also in *PAV, 2,* 215–219.

cance of the reaction principle": the principle of the equality of action and reaction would now have general application as the "inertia law of energy."[50] Planck noted further that it is possible to speak of a momentum flow as one speaks of energy flow. Energy is a scalar and energy flow a vector. By analogy, since momentum is a vector, momentum flow must be a triple tensor. When Planck examined this tensor, he recognized that it was identical with the well-known Maxwell tension, a concept that had hitherto resisted physical interpretation.

After his 1908 paper Planck made few new contributions to the theory of relativity.[51] Instead, he frequently referred to it in his philosophical and popular addresses and essays. Planck continued to have reservations about the theory of relativity because of the lack of direct experimental confirmation. By 1908 Kaufmann's results had been discredited, and although A. H. Bucherer claimed that his new experimental results supported the theory of relativity he did not gain the confidence of many physicists.[52]

3. PLANCK'S PHILOSOPHICAL RESPONSE TO THE THEORY OF RELATIVITY

Planck's early theoretical work in relativity reflects the large philosophical purpose that directed all of his work in physics: "It has always seemed to me that the most important thing, the goal that guided all of my scientific endeavor, is the greatest possible simplification and unification of the physical worldview and that the first means of reaching this goal is the reconciliation of opposites through mutual fertilization and amalgamation."[53] His efforts to achieve a unified physical world picture took the form of a search for absolutes. The theory of relativity was based on an absolute, the

[50] *Ibid.*, p. 218.

[51] Planck did make a significant contribution to the dispute over the problems related to the relativistic definition of a rigid body. See S. Goldberg, *Early Response . . . , op. cit.* (note 9), pp. 111–148.

[52] C. E. Guye and C. Lavanchy, "Verification expérimentale de la formule de Lorentz-Einstein par les rayons cathodiques de grade vitesse," *Comptes Rendus, 161* (1915), 52–55.

[53] M. Planck, "Erwiderung auf die Ansprachen vom 26. April 1918 zu Max Planck's 60. Geburtstag in der Deutschen Physikalischen Gesellschaft," *PA V, op. cit.* (note 34), *3,* 327–330. Planck was replying to speeches by E. Warburg, A. Sommerfeld, M. von Laue, and A. Einstein. Unless otherwise specified all translations in this essay are by the author.

measure of the space-time continuum, and it made the velocity of light into an invariant. Planck was attracted to the theory of relativity by these aspects of it, for he quickly comprehended that the implications of such a theory might prove to be important for his search for a physical world picture.[54] The concern with invariants requires an understanding of the nature of the relative, of experience, to Planck the basis of all knowledge. In physics, experience consists of measurements. In my discussion of Planck's philosophy of nature as it found expression in his response to relativity, I shall consider his views of the role of measurement and the nature of experience and knowledge, his great concern with absolutes, and finally his physical world picture.

The Role of Experience in the Development of Physical Theories

In 1908 Planck gave the first exposition of his views on the relationship between the world of experience, the theoretical structures of physics, and the "real world" in an address on "The Unity of the Physical World Picture."[55] In this address—and in his later writings—Planck emphasized the fundamental importance of experience and measurement for science. Only through experience can man know anything about the world:

> The source of all knowledge and therefore the origin of each science is personal experience. It is the immediately given, the most real thing that we can think of, and the first point to which we connect the thought processes that constitute science. For the material with which we work in every science we receive either directly through our sense perceptions or indirectly through accounts from others, from our teachers, from writings, from books. There are no other sources of knowledge.
>
> In physics we are dealing with the experiences that are given to us by our senses of inanimate nature and that find expression in more or less exact observations and measurements. The content of

[54] M. Planck, *Wissenschaftliche Selbstbiographie, op. cit.* (note 1); see also *Scientific Autobiography . . . , op. cit.* (note 1).

[55] M. Planck, "Die Einheit des physikalischen Weltbildes," *Phys. Zs., 10* (1909), 62–75; also in *PAV, op. cit.* (note 34), *3*, 6–29; M. Planck, *Wege zur physikalischen Erkenntnis,* 4th ed. (Leipzig, 1944), pp. 1–24; cf. M. Planck, "The Unity of the Physical Universe," trans. R. Jones and D. H. Williams, in *A Survey of Physical Theory* (New York, 1960), pp. 1–40; S. Toulmin, ed., *Physical Reality* (New York, 1970).

that which we see, hear, feel is the immediately given and consequently incontestable reality.[56]

With the development of physical science, Planck continued, the laws of physics become divorced from their origin in experience and undergo a gradual deanthropomorphization. As the analytical techniques of physics improve and the understanding of physical processes deepens, anthropomorphisms disappear in two ways. First, physical knowledge is gradually unified: concepts and laws that were developed for specific phenomena are generalized until they apply to seemingly disparate fields of physics and thus unify the fields. Secondly, successive abstractions gradually remove explanatory patterns from the realm of direct experience: the physical concept of force no longer corresponds to the exertions of men and animals, the definition of color no longer describes the sensation of color.[57]

However, Planck did not agree with Ernst Mach that all physical theories are merely an attempt to organize physical experience in an economical way.[58] Planck rejected Mach's assertion that the process of deanthropomorphization in physics was due to an inclination toward "economy of thought," that is, that knowledge is gathered and organized so that a single mind can accommodate vast quantities

[56]M. Planck, "Positivismus und reale Aussenwelt," in *Wege . . . , op. cit.* (note 55), pp. 201-218, on p. 202. In translating the essay James Murphy divided it into two essays: "Is the External World Real?" and "The Scientist's Picture of the Physical World." See M. Planck, *Where is Science Going?* (New York, 1932), pp. 64–106. For other similar statements by Planck on the fundamental role of experience see *Der Kausalbegriff in der Physik* (Leipzig, 1932); "The Concept of Causality in Physics," trans. Frank Gegnor, in *Scientific Autobiography . . . , op. cit.* (note 1), pp. 121-150; "Physikalische Gesetzlichkeit im Lichte neuerer Forschungen," *Naturwissenschaften, 14* (1926), 249-261; also in *PAV, op. cit.* (note 34), *3*, 159-171; *Wege . . . , op. cit.* (note 55), pp. 156-178; "Vom Relativen zum Absoluten," *Naturwissenschaften, 13* (1925), 52-59; also in *PAV, op. cit.* (note 34), *3*, 145-158; *Wege . . . , op. cit.* (note 55), pp. 142-155; "From the Relative to the Absolute," in *Where is Science Going?*, pp. 170-200; *Neue Bahnen der physikalischen Erkenntnis* (Leipzig, 1914); also in *PAV, op. cit.* (note 34), *3*, 65-76; *Wege . . . , op. cit.* (note 55), pp. 42-53. Cf. "New Paths to Physical Knowledge," *A Survey . . . , op. cit.* (note 55), pp. 45-55; "Die Einheit . . . ," *op. cit.* (note 55); "Zwanzig Jahre Arbeit am physikalischen Weltbild," *Physica, 9* (1929), 193-223; also in *PAV, op. cit.* (note 34), *3*, 179-208.

[57]M. Planck, "Die Einheit . . . ," *op. cit.* (note 55), pp. 3-4; see also articles referred to in note 56. Planck frequently discussed deanthropomorphization in connection with the importance of sense data.

[58]For an analysis of Mach's theory of economy see J. T. Blackmore, *Ernst Mach: His Work, Life and Influence* (Berkeley, 1972), pp. 173-179.

of experience in the course of a lifetime. Mach had suggested that such a process was valuable for human survival. Planck emphatically denied that men like Copernicus, Kepler, Newton, Huygens, or Faraday had been motivated by a desire for economy of thought when they created the laws that bear their names. Instead, they were driven by their belief in the reality of the picture they created, Planck maintained.[59] He argued that the principle of economy was of little use to the practicing physicist who could not possibly know without hindsight which point of view would be the most economical, and he recommended that the principle be given a somewhat less conspicuous position. "If the physicist wants to promote his science, he must be a realist, not an economist; that is, in the changes of phenomena he must above all search for and separate out that which is permanent, unchanging, independent of the human senses. The economy of thought serves him in this as a means but not as an end. It has always been like this and will always remain so in spite of E. Mach and his supposed antimetaphysics."[60]

Planck's view of the importance of experimental data explains his caution in admitting the validity of the theory of relativity even while he was working on its elaboration. Planck found the theory too attractive and important to reject it on the basis of Kaufmann's experimental results, but his commitment to measurement and experiment was great enough to motivate the immense effort he put into reassessing Kaufmann's experiment and independently recalculating the results from Kaufmann's data. His commitment to experimental certainty similarly supported him in his refusal, in 1906, to admit to Abraham, Bucherer, and Kaufmann that Kaufmann's results had decided the issue by experiment.[61] Finally, Planck also revealed his commitment to the importance of measurement in his 1907 paper on general dynamics in repeated references to the possibility of an experimental decision on the validity of the theory of relativity through investigations of the relationship between mass and energy.[62]

Planck's work on relativity also reflects his view that measurement and experimental data are only the starting points of physical knowledge. While Planck insisted on experimental confirmation of a

[59] M. Planck, "Die Einheit . . . ," *op. cit.* (note 55), p. 23.

[60] M. Planck, "Zur Machschen Theorie der physikalischen Erkenntnis. Erwiderung," *Phys. Zs.*, *11* (1910), 1186–1190, on 1190.

[61] See above, p. 131.

[62] M. Planck, "Zur Dynamik bewegter Systeme," *op. cit.* (note 42), pp. 24–33.

new theory, he recognized other means of testing it. The logical development and internal consistency of a theory and the degree to which the theory is capable of revealing that which is "permanent, unchanging, independent of the human senses" were equally important to him. When Planck took up the task of producing the generalized laws of motion that were to replace Newton's laws,[63] he looked forward to further investigations that might reconcile the principle of relativity with observation, but he also outlined a logical method of investigation: "A physical idea that exhibits the simplicity and generality of the principle of relativity deserves to be tested in more than one way and if it is incorrect it should be driven *ad absurdum;* that can be done in no better way than by an investigation of the consequences to which it leads."[64] This manner of testing theories was not a new idea to Planck. In 1897, Planck wrote a letter to his friend Leo Graetz in which he discussed whether or not it was possible to reconcile the second law of thermodynamics with mechanics. Planck's assistant Ernst Zermelo had argued that no mechanical proof was possible, while Ludwig Boltzmann had taken the opposite position. Planck saw "only one way to reach a definitive conclusion about the question. One must embrace one of the two positions in advance and see how far one proceeds towards the light or towards the absurd."[65] Seeing "how far one proceeds towards the light or towards the absurd" was an important element in Planck's notion of the physical world picture.

Invariants and the Real World

Planck discussed the difference between the world of experience and the real world in almost every essay he wrote after 1908 on the nature of scientific knowledge. He held that reality consists of the constant elements of physical world pictures which are independent of all individual intellectual characteristics.[66] Planck was able to believe in an absolute, invariant real world because the development of physics had led to the discovery of universal physical constants such as the velocity of light, the charge and rest mass of an electron, or

[63] M. Planck, "Das Prinzip der Relativität . . . ," *op. cit.* (note 21).

[64] *Ibid.*, p. 137.

[65] Max Planck to Leo Graetz, 23 May 1897. The original letter is in the Deutschen Museum, Munich. The translation is by T. S. Kuhn. See T. S. Kuhn, *Blackbody Theory and Quantum Discontinuity, 1894–1912* (forthcoming). Cf. H. Kangro, *Vorgeschichte des Planckschen Strahlungsgesetzes* (Wiesbaden, 1970), esp. pp. 128–131.

[66] M. Planck, "Die Einheit . . . ," *op. cit.* (note 55), pp. 20–22.

the elementary quantum of action[67] and of universal physical laws. The universal constants were the result of a great number of measurements, and one could be certain that future measurements would give the same numerical values for them within the limits of experimental error. They were independent of individual experience. Planck found it impossible that any "real physicist," knowing of the existence of the universal physical constants, could espouse positivism. "Physical science demands the assumption of a real world that is independent of us and that we can never, to be sure, know directly, but that we can always perceive only through the eyeglasses of our sense perceptions and through the measurements that they allow us to make."[68] The universal physical constants may never be precisely known or may some day have to yield to higher absolute concepts, Planck noted, but the quest for invariants is still the ideal, indeed the highest, purest motivation for doing physical science. It is the search for the absolute.[69]

Planck's concern with absolutes did not conflict with his efforts on behalf of the theory of relativity. Planck held that every relative is necessarily connected to an absolute. The denial of the absolute nature of space and time in the theory of relativity does not, he argued, eliminate the absolute; it locates the absolute beyond space and time in the metric of the four-dimensional manifold in which space and time have been fused into a uniform continuum by means of the velocity of light.[70] The metric, Planck claimed, possesses a transcendental character entirely independent of all arbitrary choices such as measuring processes or reference systems that determine space and time.[71]

[67]M. Planck, "Die Stellung der neueren Physik zur mechanischen Naturanschauung," *Phys. Zs.*, *11* (1910), 922–932; also in *PAV*, *op. cit.* (note 34), *3*, 30–46; *Wege . . .* , *op. cit.* (note 55), 25–41; cf. "The Place of Modern Physics in the Mechanical View of Nature," in *A Survey . . .* , *op. cit.* (note 55), pp. 27–44.

[68]M. Planck, *Religion und Naturwissenschaft* (Leipzig, 1938); also in *Wege . . .* , *op. cit.* (note 55), pp. 291–307, on p. 300; cf. "Religion and Science," *Scientific Autobiography . . .* , *op. cit.* (note 1), pp. 151–187, on p. 173.

[69]M. Planck, "Vom Relativen . . . ," *op. cit.* (note 56), 158.

[70]M. Planck, "Vom Relativen zum Absoluten," *op. cit.* (note 56), p. 153.

[71]*Ibid.* See also "Kausalgesetz und Willensfreiheit," (1923), in *Wege . . .* , *op. cit.* (note 55), p. 128. This essay was translated as two separate essays by James Murphy in M. Planck, *Where is Science Going?* (New York, 1932): "Causation and Free Will: The Problem Stated," pp. 107–140, and "Causation and Free Will: The Answers of Science," pp. 141–169.

Planck considered the invariants in the theory of relativity of overriding importance. In his 1907 paper on general dynamics Planck concluded the central part of the paper by listing the invariants that his theory had produced.[72] Again, in his 1909 lectures on theoretical physics at Columbia University, Planck devoted a considerable part of the lecture on relativity to a discussion of the physical quantities that the theory showed to be invariant: the action, the Lagrangian density, the entropy, and the pressure of a system. Other physicists, for example Poincaré, had noted the existence of such invariants,[73] but only Planck accorded them so much prominence.

The second class of constituents of the real world that Planck postulated, the true laws of the universe, were as absolute and unchanging to him as the universal physical constants. Empirical laws were to him merely approximations to these absolute laws which were exact laws and universally valid with respect to place and time. The first such law, Planck once said, which he knew with certainty to possess absolute independent validity was the law of the conservation of energy. Even as an old man, Planck still recalled his gymnasium teacher's concrete account of it.[74]

Of all the quantities that remained invariant under the theory of relativity, perhaps the most important to Planck was the principle of least action:

> The most brilliant achievement of the principle of least action is shown by the fact that Einstein's theory of relativity, which has robbed so many theorems of their universality, has not disproved it, but has shown that it occupies the highest position among physical laws. The reason for this is that Hamilton's "action" . . . is an invariant with respect to all Lorentz transformations, that is, it is independent of the system of reference of the observers. . . .
>
> As in the case of the principle of least action, the principle of the conservation of energy has also a special position in the theory of relativity. Energy is, however, not an invariant with reference to the Lorentz transformations any more than it was earlier with respect to the Galilean transformations. . . . The principle of least action stands superior to both [conservation of energy and con-

[72] M. Planck, "Zur Dynamik bewegter Systeme," *op. cit.* (note 42), p. 23.

[73] H. Poincaré, *op. cit.* (note 23).

[74] M. Planck, *Wissenschaftliche Selbstbiographie, op. cit.* (note 1), pp. 7–8; *Scientific Autobiography . . . , op. cit.* (note 1), pp. 13–14.

servation of momentum], even when considered together, and it appears to govern all reversible processes in Nature. . . .[75]

Planck showed that one can derive the conservation of energy principle from the principle of least action, but that one cannot do the converse. The reason for this is that the conservation of energy principle provides only one equation, while the principle of least action provides as many equations as there are variables.[76]

Planck's position on the validity of the theory of relativity gradually changed from early noncommittal statements[77] to an expression of hope for future experimental confirmation in 1910.[78] However, Planck was drawn to the theory by its invariants,[79] and it is safe to assume that it was these, and especially the invariance of the principle of least action, that most inspired Planck with the belief in the eventual validation of the theory of relativity.

Planck's Physical World Picture

Planck first discussed the physical world picture in his 1908 Leiden lecture on "The Unity of the Physical World Picture."[80] These early remarks lack the clarity with which he defined the con-

[75]M. Planck, "Das Prinzip der kleinsten Wirkung," *Kultur der Gegenwart*, Part 3, Division 3, Vol. 1, E. Warburg ed., *Physik* (Leipzig, 1915), pp. 692–702; also in *Wege . . . , op. cit.* (note 55), pp. 68–78; *PAV, op. cit.* (note 34), *3,* 91–101. All references will be to *Wege. . . .* The quote is on pp. 77–78. Cf. "The Principle of Least Action," *A Survey . . . , op. cit.* (note 55), pp. 69–81, esp. pp. 80–81. The translation is by R. Jones and D. H. Williams. See also M. Planck, *Acht Vorlesungen über Theoretische Physik* (Leipzig, 1910), pp. 97–98.

[76]*Ibid.*

[77]M. Planck, "Bemerkungen . . . ," *op. cit.* (note 49).

[78]M. Planck, "Die Stellung . . . ," *op. cit.* (note 67), p. 929.

[79]M. Planck, *Wissenschaftliche Selbstbiographie, op. cit.* (note 1), p. 32; *Scientific Autobiography . . . , op. cit.* (note 1).

[80]Planck discussed the concept of the physical world picture in the following essays: "Die Einheit . . . ," *op. cit.* (note 55); "Die Stellung . . . ," *op. cit.* (note 67); "Physikalische Gesetzlichkeit . . . ," *op. cit.* (note 56); "Die Kausalität in der Natur," in *Wege . . . , op. cit.* (note 55); "Erwiderung . . . ," *op. cit.* (note 53); *Der Kausalbegriff . . . , op. cit.* (note 56); "Vom Relativen zum Absoluten," *op. cit.* (note 56); *Neue Bahnen . . . , op. cit.* (note 56); "Zwanzig Jahre . . . ," *op. cit.* (note 56); "Theoretische Physik," *PAV, op. cit.* (note 34), *3,* 209–218; "Sinn und Grenzen der exakten Wissenschaft" (1941), in *Wege . . . , op. cit.* (note 56); pp. 323–339; see also "The Meaning and Boundaries of Exact Science," in *Scientific Autobiography . . . , op. cit.* (note 1), pp. 80–112.

cept later, but they show that Planck was thinking of an ultimate intellectual picture of the physical universe. The physicist, he explained, derives his knowledge from experience and from "physical thinking": he uses his observations to draw conclusions that can never be tested by other direct observations. Through physical thinking, through the generalization of experience, the physicist arrives at knowledge that is not verifiable in experience, but that nonetheless corresponds to what Planck called reality. The physical world picture, Planck asserted, was of the nature of such knowledge. It was not an arbitrary invention of the human intellect, but the reflection of real processes in nature that are independent of man.[81] Planck's assertion of the validity of the physical world picture rested on his belief that the same laws that govern external nature also govern the workings of the mind. Planck frequently referred to this argument and he employed the strategy it supported in his theoretical work on the theory of relativity.

The principal characteristic of the physical world picture that Planck sought was its unity. All observed physical phenomena had to be included.[82] Planck did not claim that any of the competing worldviews of the period represented the ultimate solution. The "constant, unified world picture" was still only the goal "that true natural science approaches through all its changes."[83] World pictures had succeeded each other through the centuries according to the same process of change:

> It must be noted that the continual displacement of one world picture by another is dictated by no human whim or fad, but by an irresistible force. Such change becomes inevitable whenever scientific research hits upon a new fact in nature for which the currently accepted world picture cannot account. To cite a concrete example, such a fact is the velocity of light in empty space and another is the part played by the elementary quantum of action in the regular occurrence of atomic processes. These two facts, and many more, could not be incorporated in the classical world picture, and consequently its framework had to be destroyed and a new world picture was introduced in its place.
>
> This in itself is enough to make one wonder. But the circumstances which call for even greater wonderment, because it is not

[81] M. Planck, "Die Einheit . . . ," *op. cit.* (note 55), p. 25.
[82] *Ibid.*, p. 24.
[83] *Ibid.*, p. 27.

> self-evidently a matter of course by any means is that the new world picture does not wipe out the old one, but permits it to stand in its entirety and merely adds a special condition to it. . . . In fact, the laws of classical mechanics continue to hold satisfactorily for all processes in which the velocity of light may be considered to be infinitely great, and the quantum of action to be infinitely small.[84]

Planck noted the contradiction that, although new observations had led to improvements and simplifications of the physical world picture, it still continuously moved further away from the world of sense perceptions, that is, it became less and less anthropomorphic. This move from the world of experience was nothing other than a move toward the real world.[85]

In 1908 Planck believed that the ultimate physical world picture was close at hand, perhaps because he still shared in the *fin de siècle* feeling that the major task of physics was completed.[86] The deanthropomorphized world picture that he anticipated might appear "colorless and drab," especially when compared with vivid earlier world pictures, but it would have the desirable "unity of all separate parts of the picture, unity of space and time, unity of all investigators, nations, and cultures."[87]

Following his 1908 paper and over the next twenty years Planck repeatedly introduced the concept of the physical world picture in his public lectures. In 1929 Planck returned to the theme with great clarity and sureness. The evidence suggests that Planck did not change his mind very much during this twenty year period; rather he now gave his formerly intuitive and incomplete ideas a precise formulation.[88]

As in his earlier work Planck asserted the existence of three separate worlds: the world of sense perceptions, the inaccessible real world, and the physical world picture. The first two of these were worlds

[84] M. Planck, "The Meaning and Boundaries . . . ," *op. cit.* (note 80), pp. 97–98.

[85] M. Planck, "Zwanzig Jahre . . . ," *op. cit.* (note 56), pp. 184–185.

[86] On attitudes toward the state of physics at the end of the nineteenth century see Lawrence Badash, "Completeness of Nineteenth Century Science," *Isis, 63* (1972), 48–58, and the literature cited there. With regard to Planck see especially pp. 54–55.

[87] M. Planck, "Die Einheit . . . ," *op. cit.* (note 55), p. 18.

[88] M. Planck, "Zwanzig Jahre . . . ," *op. cit.* (note 56).

outside the control of man, but the physical world picture was for Planck a conscious, purposeful creation of the human spirit and as such changeable and subject to development. The physical world picture had the two-fold task of making known the real world as completely as possible and of describing the world of sense perceptions in as simple terms as possible. Planck added that it would be useless to decide for the one or the other of the two aspects of the task; each, taken by itself, is unsatisfactory. On the one hand physicists can never have direct knowledge of the real world, and, on the other hand, they will never be able to decide which description of natural phenomena is the simplest. The main thing, he insisted, is that the two aspects of the task that he had assigned to the physical world picture never contradict each other, but rather complement each other.[89]

Depending on whether physicists inclined toward the first or toward the second aspect of the task they were metaphysicians or positivists, Planck claimed. Physicists who were neither but who sought instead to uncover the inner completeness and the logical structure of the physical world picture Planck identified as "axiomatizers."[90] Each of these groups of physicists became influential at different times in the history of science. In periods when the physical world picture displays a stable character, such as, in Planck's view, the second half of the nineteenth century, physicists may conclude that they are closer to understanding the real world. During periods of uncertainty and change positivism comes to the fore, and the world of experience is seen as the only secure basis for physical research.[91]

The transformations of physical world pictures did not take place in rhythmical oscillations, Planck held, but in a determined direction marked by a constant increase of the content of man's world of experience, of his understanding of this world, and of his control over it.[92] Theoretical physics might give "the impression of an old and honored building which is falling into decay with parts tottering one after the other and its foundation threatening to give way," Planck noted in 1910, but that conception was erroneous and, although great changes were in fact taking place, they were only extensions and perfections of the structure.[93] Planck's historical reconstructions of

[89]*Ibid.*, p. 182.
[90]*Ibid.*, p. 183.
[91]*Ibid.*
[92]*Ibid.*, p. 184.
[93]M. Planck, "New Paths . . . ," *op. cit.* (note 56), p. 45.

the development of the theory of relativity in which he insisted on an evolutionary rather than a revolutionary development reflect the same view of the nature of change in physical world pictures. Moreover, Planck's analysis of the logic of the theory of relativity and of its logical relationship to other theories stressed the view that the introduction of the theory of relativity was one more step in the evolution of the physical world picture.

> The principle of relativity by no means simply disintegrates and demolishes—it only throws aside a form that through the continuous enlargement of science was already ruptured—but to a much greater degree it orders and builds. In place of the old building that has become too small it erects a new, more comprehensive and durable one which contains all of the treasures of the old . . . in changed, clearer arrangements. . . . It removes from the physical world picture the inessential ingredients arbitrarily introduced by our . . . habits and thereby cleanses physics of the anthropomorphical impurities originating from the individuality of the physicist. . . .[94]

The application of the principle of relativity to mechanics led to a modification of Newton's laws of motion, which were no longer invariant in four-dimensional coordinate systems, and thus to a generalization and simplification of Newtonian mechanics.[95]

When Planck spoke of the unity of the physical world picture, he meant the reduction of all physical phenomena to one basic law. Planck believed that that law was the principle of least action.

> For as long as physical science has existed it has had before it as its highest, worthiest goal the solution of the problem of uniting all observed and still to be observed natural phenomena in a single, simple principle which permits us to calculate both past and especially future processes from present ones. It is in the nature of things that this goal has not yet been attained nor ever will be completely attained. But it is indeed possible to approach it more and more, and the history of theoretical physics shows that in this way a large number of important successes could be obtained which clearly speak in favor of the view that the ideal problem is not a purely utopian, but rather an eminently fruitful one, and

[94] M. Planck, "Die Stellung . . . ," *op. cit.* (note 67), p. 932.
[95] M. Planck, "Theoretische Physik," *op. cit.* (note 80), p. 214.

that it therefore deserves to be always kept in mind, especially with regard to application.

Among the more or less general laws that mark the achievements of physical science in the development of the last centuries, the principle of least action today is probably that which by form and content may claim to come closest to the ideal goal of theoretical research.[96]

In 1906, in an exchange with Bucherer relating to the theory of relativity, Planck first indicated how much importance he attached to the principle of least action in this connection. He advised Bucherer to investigate whether or not the principle could be accommodated by Bucherer's new theory, since the equations of motion of electrons would be reduced to those of general mechanics through the Lagrangian form.[97] A year later, in a letter to Einstein written shortly after the presentation of his new general dynamics based on the principle of least action and the principle of relativity, Planck sought Einstein's advice on "urgent" questions about the principle of least action and its bearing on the admissibility of Einstein's principle of relativity. Planck informed Einstein that Bucherer had privately told him without proof or explanation that the principle of relativity was incompatible with the principle of least action. Planck was pleased to learn that Einstein did not share Bucherer's view.[98] In his 1929 address on the physical world picture Planck concluded that the introduction of the theory of relativity into the physical world picture was "one of the most important

[96] M. Planck, "Das Prinzip der kleinsten Wirkung," *op. cit.* (note 75), p. 68.

[97] M. Planck, "Die Kaufmann'schen Messungen . . . ," *op. cit.* (note 22).

[98] Max Planck to A. Einstein, Grunewald [Berlin], 6 July 1907. This letter is in the possession of the Einstein Archives, Princeton University, to whom I am indebted for permission to use it. I am particularly grateful to Helen Dukas who generously provided me with a typescript copy of the handwritten original.

Bucherer had a penchant for making strong assertions with little or no documentation, not only in his private letters, but in his published papers as well. This led him into some rather dramatic, public, polemical debates, notably with E. Cunningham in England during 1907–1908, a period when Bucherer rejected the theory of relativity on any grounds he could find: it did not conform to experiment, it was a misguided attempt to modify Maxwell's equations, it violated electromagnetic assumptions, and, as in this case, it was at odds with the principle of least action. In 1908 he changed his mind suddenly, apparently solely on the basis of his own experiments. Ironically, challenges to his experimental results by A. Bestelmeyer led him into yet another acrimonious public debate. Cf. S. Goldberg, *Early Response . . . , op. cit.* (note 9), pp. 97ff.

steps toward its unification and completion."[99] The contribution of the theory of relativity toward unity lay in no small part in confirming the principle of least action as the most general of all physical principles and thus establishing one of the unifying elements of Planck's vision of the ultimate physical world picture.

In 1908 Planck believed that the developing physical world picture now consisted of only two remaining major divisions: matter and ether. He was hoping that the two divisions would soon merge as the physical world picture neared completion.[100] Between 1907 and 1910 the problem of matter and ether caused him considerable agitation. In his letters to Lorentz he constantly came back to the question. On 1 April 1908 Planck wrote to Lorentz that given that experience tells us that there exists a true equilibrium for the finite distribution of energy between matter and ether, the electron theory must include a hypothesis that prevents the transformation of all energy from matter into ether over a period of time. He repeated what he had written to Einstein in July 1907: the simple Maxwell equations have to be retained for the free ether.[101] A year later[102] Planck wrote to Lorentz that, if the quantum of action is indeed a constant of the ether, the question arises whether or not Maxwell's equations are still applicable to free ether. The answer is no. Therefore Planck concluded once again that the quantum of action has nothing to do with processes in free ether. Planck continued to be concerned with Einstein's suggestions about the quantization of light energy. Again and again the problem of the possible interaction between the ether and the quantum resonators came up in Planck's letters to Lorentz.[103]

[99] M. Planck, "Zwanzig Jahre . . . ," *op. cit.* (note 56), p. 187.

[100] M. Planck, "Die Einheit . . . ," *op. cit.* (note 55).

[101] M. Planck to H. A. Lorentz, 1 April 1908. I am indebted to Stephen Brush, University of Maryland, who kindly provided me with a microfilm copy of selected correspondence of Lorentz which is available at the Hague. A copy of the same microfilm is on file with the Niels Bohr Library at the American Institute of Physics in New York.

[102] Planck to Lorentz, 16 June 1909.

[103] Besides the letters already cited, the reader is directed in particular to the letter from Planck to Lorentz dated 7 October 1908. In his letter Planck considers Lorentz' suggestion that the quantum resonators are not the same as ordinary matter and that the role of the molecules of ordinary matter is to transmit energy between the resonators. Planck was not happy with the idea. In the absence of ordinary matter the ether would play the role of transmitter and this conception did violence to the absolutely fixed ether which obeyed Maxwell's equations "exactly."

Planck's letters to Lorentz reveal his casual use of the concept of the ether and his resistance to achieving a more profound understanding of the problems involved. Planck understood the impossibility of action at a distance. He was not willing to blend the notions of the ether and the quantum of action, as attractive as the idea might be for a unified physical world picture. Lorentz and Planck agreed that it was highly unlikely that light quanta could maintain their individuality while propagating through free ether.[104] Furthermore, Planck argued that adopting the quantum hypothesis for light would invalidate the theories of interference, refraction, and diffraction. He encountered great difficulties in reconciling the notion of a coupling constant between, say, ether and electrons with the traditional concept of "free ether." He even toyed with the assumption that energy exchanged between electrons and the free ether could only occur in units of $h\nu$. Writing to Lorentz in July 1909, Planck remarked on the differences in their interpretation of h. Lorentz, Planck pointed out, interpreted h in such a way that the degrees of freedom of the ether are limited, so that every degree of freedom of the ether can assume energy only in multiples of h. Planck claimed exactly the opposite, namely that the electrons give up their energy in multiples of h. "From your point of view [Planck wrote], the unyielding point is the ether, from my point of view, it is the electrons."[105]

In 1907 Planck was still seriously considering the possibility of measuring the motion of the earth relative to the ether. In a letter to Lorentz dated 19 October 1907, six months after he had delivered his paper on general dynamics, Planck stated that he was occupied with the investigation of a method for measuring the influence of the motion of the earth on the intensity of radiation of a blackbody. He had little hope that the experiment would be practical: "If only $(v/c)^2$ were not so absurdly small! It is a real pity."[106]

By 1910 he had abandoned such hopes not only on practical grounds, but on theoretical ones as well. The principle of relativity, he now said, forced the abandonment of the concept of the rest ether as a substantive carrier of electromagnetic waves. The ether had to be

[104] Planck to Lorentz, 16 June 1908.

[105] Planck to Lorentz, 10 July 1909. "Bei Ihnen liegt . . . die Hartnäckigkeit beim Aether, bei mir bei den Elektronen."

[106] Planck to Lorentz, 19 October 1907. "Wenn nur $(v/c)^2$ nicht so unsinnig klein wäre! Es ist ein wahrer Jammer."

replaced by the concept of an absolute vacuum without physical properties in which electromagnetic energy is continuously propagated. The speed of propagation of the electromagnetic energy could not be considered a property of the absolute vacuum, but rather a property of the electromagnetic energy itself. "Where there is no energy, there exists no propagation velocity either."[107]

Planck was not rejecting the concept of the ether but replacing it by the concept of an absolute vacuum. His substitution was similar to the transformations of the ether concept by Lorentz and Poincaré. Planck often used the terms "ether" and "vacuum" interchangeably.[108] He sometimes thought it desirable to relinquish the ether concept entirely because of the difficulties it presented, but as late as 1946 he was only willing to reject the study of the mechanical properties of the ether, not the ether itself.[109]

4. CONCLUSION

Although Planck was intimately associated with the two major innovations in physics in the twentieth century, quantum physics and relativistic physics, he never intended to participate in a revolution in physics. As M. J. Klein has pointed out with regard to quantum physics, Planck tried throughout his career to reconcile the quantum hypothesis with classical physics.[110] He took the same approach to the theory of relativity.

Planck expressed his sense of continuity in the first sentence of his 1906 paper on relativistic generalization of the laws of dynamics where he described the principle as "recently introduced by Lorentz and in a more general form by Einstein.[111] In his reassessment of the Kaufmann data Planck referred to the "Lorentz-Einstein theory in which the principle has exact validity." He added that for the sake of convenience he would call this theory the theory of relativity in the remainder of the article, but during the discussion following the presentation of the paper Planck again referred to the "Lorentz-Einstein theory" which takes as a basic postulate that no absolute

[107] M. Planck, *Acht Vorlesungen . . . ,*" *op. cit.* (note 75), pp. 116–117. The quotation is on p. 117.

[108] *Ibid.,* pp. 110 ff.; see also, "Die Stellung . . . ," *op. cit.* (note 67).

[109] M. Planck, *Scheinprobleme der Wissenschaft* (Leipzig, 1947), p. 7.

[110] M. J. Klein, *op. cit.* (note 2).

[111] M. Planck, "Das Prinzip der Relativität . . . ," *op. cit.* (note 21).

translation is detectable.[112] His first reference to Einstein's theory of relativity occurred in his analysis of the principle of action-reaction in 1908.[113] In 1910 Planck described Lorentz, Einstein, and Minkowski as among the "pioneers" who worked with the new concept of relativity: Lorentz discovered the concept of relative time and introduced it into electrodynamics without, however, drawing any radical consequences from it, Einstein proclaimed the relativity of time as a universal postulate, and Minkowski then fashioned a consistent mathematical system of relativity theory.[114] Planck described the origin of the theory of relativity as typical of the origin of all scientific theories in the sense that it had been the result of a contradiction between theory and experiment. Such a contradiction represents progress, for it leads to changes or improvements in existing theory that may affect other parts of physics as well and even affect the development of physics far more than could have been foreseen.[115]

Planck was equally conservative in his use of the theory of relativity in his early work on the subject. He almost never referred explicitly to the second postulate of the theory, the invariance of the speed of light; in fact, he never spoke of the invariance of the speed of light as a postulate. Rather, he considered it a consequence of the principle of relativity.[116] In 1926 Planck remarked that the work of elaborating the theory of relativity, of developing its con-

[112]M. Planck, "Die Kaufmannschen Messungen . . . ," *op. cit.* (note 22), pp. 756, 761.

[113]M. Planck, "Bemerkungen . . . ," *op. cit.* (note 49).

[114]M. Planck, "Die Stellung . . . ," *op. cit.* (note 67), p. 927.

[115]M. Planck, "Sinn und Grenzen . . . ," *op. cit.* (note 80), pp. 336ff.

[116]Planck gave his first full account of his view of the import of the invariance of the speed of light in his Columbia University lectures, *Acht Vorlesungen . . . , op. cit.* (note 75).

There has been considerable discussion in the literature over the years of how Einstein first conceived of the theory of relativity and how in the development of the theory he saw the relationships between the two postulates and their consequences, the Lorentz transformation equations, and the various kinematical relationships that the transformations entail. Historians obtained most of the evidence employed in that discussion from Einstein's first paper on relativity in 1905 and his recollections in the autobiographical sketch he wrote much later. Cf. A. I. Miller, *op. cit.* (note 19), esp. pp. 41–43 and the literature cited there. Without wanting to reconstruct how Einstein created the theory, I recommend his *Relativity: the Special, the General Theory* (New York, 1918) as a good source for his view of the logical relationship of the parts of the theory.

sequences for the purpose of testing its validity—work in which he had had a large share—was made easier because the assertions made by the theory fitted classical physics perfectly. He went on to state that, if he were not stopped by historical considerations, he would not hesitate for a second to consider the theory of relativity a part of classical physics.[117]

In several of his addresses Planck spoke of the close correspondence between universal physical laws and ethics. His remarks there prove that his conservative approach to the theory of relativity as well as his loyalty to it stemmed not only from his scientific and philosophical convictions but also from his ethical beliefs. Unfortunately, the problem of the connections between scientific achievements and ethical or psychological motivations is too elusive and too complex to be developed here. We catch a glimpse of these inner connections in Einstein's words at the celebration of Planck's sixtieth birthday:

> Man tries to make for himself, in the fashion that suits him best, a simplified and intelligible picture of the world; he then tries to some extent to substitute this cosmos of his for the world of experience and thus to overcome it. This is what the painter, the poet, the speculative philosopher, and the natural scientist do, each in his own fashion. Each makes this cosmos and its construction the pivot of his emotional life, in order to find in this way the peace and security that he cannot find within the all-too-narrow realm of swirling personal experience. . . .
>
> The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction. There is no logical path to these laws; only intuition, resting on sympathetic understanding, can lead to them. . . . The longing to behold [cosmic] harmony is the source of the inexhaustible patience and perseverance with which Planck has devoted himself . . . to the most general problems of our science. . . . The state of mind that enables a man to do work of this kind is akin to that of the religious worshipper or the lover; the daily effort comes from no deliberate intention or program, but straight from the heart.[118]

117M. Planck, "Physikalische Gesetzlichkeit . . . ," *op. cit.* (note 56), p. 167.

118Quoted in Banesh Hoffmann, *Albert Einstein: Creator and Rebel* (New York, 1972), on p. 222. Hoffmann remarks that these words also reveal a great deal about Einstein. Cf. G. Holton, "Mach, Einstein and the Search for Reality," *op. cit.* (note 7).

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