

(10). As described above, the severely opisthopic condition of their pelvis is consistent with the notion that these birds roosted in trees. In contrast, based primarily on disputed measurements of claw curvature, *Archaeopteryx* has been interpreted as adapted primarily for a terrestrial rather than an arboreal existence (18). However, as in the enantiornithines, the morphology of *Archaeopteryx*'s pelvis is best interpreted as adapted for a largely, if not exclusively, arboreal existence.

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Belated Decision in the Hilbert-Einstein Priority Dispute

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According to the commonly accepted view, David Hilbert completed the general theory of relativity at least 5 days before Albert Einstein submitted his conclusive paper on this theory on 25 November 1915. Hilbert's article, bearing the date of submission 20 November 1915 but published only on 31 March 1916, presents a generally covariant theory of gravitation, including field equations essentially equivalent to those in Einstein's paper. A close analysis of archival material reveals that Hilbert did not anticipate Einstein. The first set of proofs of Hilbert's paper shows that the theory he originally submitted is not generally covariant and does not include the explicit form of the field equations of general relativity.

It took Einstein 8 years, from 1907 to 1915, to complete the general theory of relativity, based on the field equations

$$R_{\mu\nu} = -\kappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right) \quad (1)$$

where $g_{\mu\nu}$ is the metric tensor representing the gravitational potentials, $R_{\mu\nu}$ is the Ricci tensor, κ is a constant, $T_{\mu\nu}$ is the stress-energy tensor of matter, and T is its trace. The principal difficulty he had to overcome

was finding the right balance between the mathematical implications of a generalized principle of relativity and physical requirements such as the existence of a Newtonian limit (1, 2). Hilbert, on the other hand, only began to work seriously on gravitation in mid-1915. Concerning physics, his interests had focused since the end of 1912 on the structure of matter, and in particular, since mid-1913, on Gustav Mie's special-relativistic electromagnetic theory of matter. Then, after Einstein's visit to Göttingen in the summer of 1915, Hilbert attempted to forge a synthesis between Mie's theory and Einstein's approach to gravitation based on $g_{\mu\nu}$ (3, 4).

A recent comprehensive Einstein biography, which shows promise of becoming the standard reference, offers a succinct

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summary of the presently accepted account of the almost simultaneous formulation of the field equations by Einstein and Hilbert (5):

In the decisive phase [of work on general relativity] Einstein even had a congenial colleague, though this caused him more annoyance than joy, as it seemed to threaten his primacy. "Only one colleague truly understood it, and he now tries skillfully to 'nostrify' [that is, appropriate] it," he complained to [Heinrich] Zangger about what he evidently regarded as an attempt at plagiarism. This colleague was none other than David Hilbert. . . . What must have irritated Einstein was that Hilbert had published the correct field equations first—a few days before Einstein. [. . .]

In November, when Einstein was totally absorbed in his theory of gravitation, he essentially corresponded only with Hilbert, sending Hilbert his publications and, on November 18, thanking him for a draft of his article. Einstein must have received that article immediately before writing this letter. Could Einstein, casting his eye over Hilbert's paper, have discovered the term which was still lacking in his own equations [the trace term $-1/2g_{\mu\nu}R$ (6)], and thus 'nostrified' Hilbert?

Fölsing is convinced, in agreement with the presently accepted view among physicists and historians of science, that Einstein's and Hilbert's achievements were actually parallel and independent, with the priority in submitting the field equations in their final form going to Hilbert (7). If, however, the standard account were correct, it would seem quite possible that indeed Einstein "nostrified" from Hilbert the critical trace term, still missing from the field equations in the paper he submitted on 11 November (8). Hilbert's published paper is mathematically complex and might have been difficult for Einstein to fully digest so quickly, but it does clearly display the field equations of general relativity, including the critical trace term [(3), p. 404]. Although this possible conclusion from the accepted view usually is not drawn, the arguments by which Einstein is exculpated are rather weak, turning on his slowness in fully grasping Hilbert's mathematics (5).

In the course of a project on the history of general relativity at the Max Planck Institute for the History of Science, archival work by Corry brought to light a hitherto unnoticed set of proofs of Hilbert's paper (9). Detailed analysis and comparison of these proofs with both published versions of Hilbert's paper (10) and with Einstein's papers on gravitation from 1913 to 1915 (2) enabled us to construct an account of the crucial weeks in November 1915 that radically differs from the standard view, excludes the possibility that Einstein plagiarized from Hilbert the last crucial step in completing general rela-

tivity and sheds new light on Einstein's complaint of "nostrification" by Hilbert.

Both the proofs and the final version of Hilbert's first communication (3) are dated "submitted on 20 November 1915," presumably referring to the original manuscript. A copy of the proofs, preserved in his archives and marked in his own hand "First proofs of my first note," bears a printer's stamp dated 6 December 1915 (Fig. 1). However, the cover of the issue in which the heavily revised published version appeared is dated 31 March 1916. Its first note cites Einstein's conclusive paper, in which he reached the

final form of his generally covariant theory (11), submitted on 25 November 1915 and published on 2 December 1915. Thus, Hilbert could have revised his paper in response to Einstein's work.

Differences between the proofs and this published version of Hilbert's paper confirm this view. Two of the differences, in particular, are fundamental.

1) In the proofs, Hilbert asserts that his theory cannot be generally covariant. In addition to 10 generally covariant equations, there must be four additional noncovariant equations to guarantee causality (12):

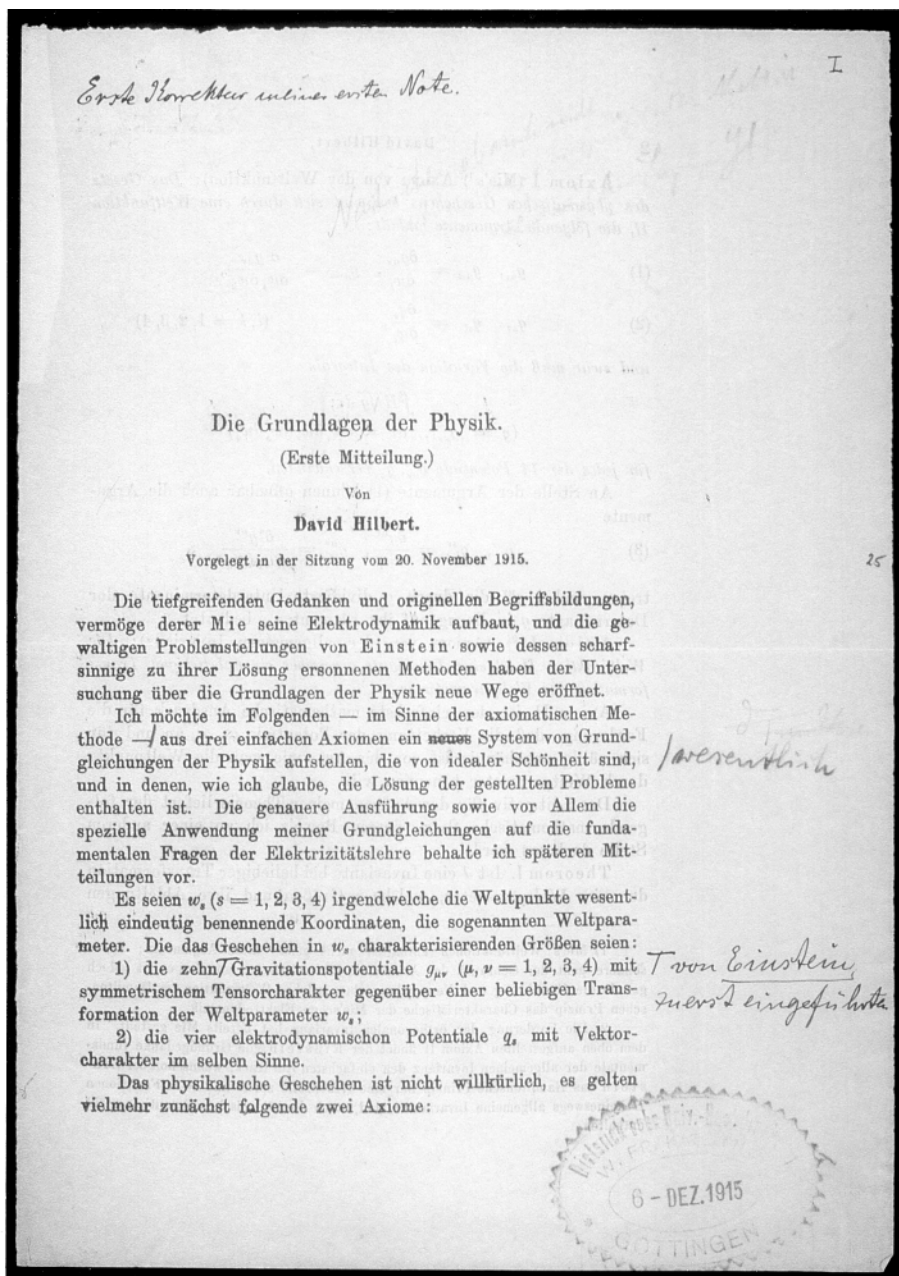


Fig. 1. The first page of a set of proofs of Hilbert's first communication, with Hilbert's handwritten corrections and a printer's stamp, dated 6 December 1915. [Reproduced with permission by the Staats- und Universitätsbibliothek Göttingen (Handschriftenabteilung), Germany]

Since our mathematical theorem shows that the previous axioms I and II can only provide ten essentially independent equations for the 14 potentials [of gravitation and electromagnetism]; and further, maintaining general covariance makes quite impossible more than ten essentially independent equations for the 14 potentials $g_{\mu\nu}$, q_s ; then, in order to keep the deterministic characteristic of the fundamental equations of physics, in correspondence with Cauchy's theory of differential equations [that is, to have a well-posed Cauchy problem], the requirement of four further non-invariant equations to supplement [the generally covariant gravitational equations] is unavoidable. In order to find these equations I start out by setting up a definition of the concept of energy.

After setting up an equation that he calls "the energy theorem," Hilbert introduces a third axiom (13):

Axiom III (axiom of space and time). The space-time coordinates are those specific world parameters for which the energy theorem . . . is valid. Using this axiom, space and time provide in fact a labelling of the world points for which the energy principle is valid.

The validity of [the energy] equation . . . is a consequence of axiom III: these four differential equations . . . supplement the [generally covariant] gravitational equations . . . to yield a system of 14 equations for the 14 potentials $g^{\mu\nu}$, q_s : the system of the fundamental equations of physics.

Note that Hilbert distinguishes here between the world parameters, which are arbitrary, and the space-time coordinates, which are not. Here he follows Einstein's earlier argument against general covariance from his papers of 1913 to 1915. Einstein then justified his theory's lack of general covariance and the need to select "adapted coordinate systems" on the same grounds of causality and energy-momentum conservation.

Hilbert abandoned this entire argument in the published version of his first communication. In a letter to Felix Klein (14), he remarked with regard to the role of the energy theorem in the proof version of his theory, "But I later suppressed the whole thing because the thing did not appear mature to me." In his second communication, published in 1917 (15), Hilbert gave a radically different definition of causality for a generally covariant theory, essentially the one accepted today (16). He there critically notes the noncovariant nature of Einstein's earlier work, characteristic also of his own version in the proofs: "In his original, now abandoned theory Einstein indeed postulated four non-invariant equations for the $g_{\mu\nu}$ in order to save the causality principle in its old form" (15). Hilbert's revised definition of causality for generally covariant theories led him to explicitly reject the possibility of the coordinates being physically significant. In the 1924 version of his first communica-

tion, he described axiom II, the requirement of general covariance, for the first time as "the simplest mathematical expression for the requirement that the coordinates in themselves have no sort of physical significance . . ." [(10), p. 4].

2) In the proofs of his first communication, Hilbert's world function includes a gravitational term $\sqrt{g}K$ (17) and indicates that the gravitational part of the field equations takes the form of the variational derivative of the gravitational term with respect to the metric. Hilbert does not, however, give the explicit form of this gravitational part of the field equations. In the published version, on the other hand, he explicitly writes down the expression for the variational derivative [(3), p. 404]

$$[\sqrt{g}K]_{,\mu\nu} = \sqrt{g} \cdot \left(K_{,\mu\nu} - \frac{1}{2} K g_{\mu\nu} \right) \quad (2)$$

justifying his expression by the argument [(3), pp. 404–405]

. . . which follows easily without calculation from the fact that, except for $g_{\mu\nu}$, $K_{,\mu\nu}$ [the Ricci tensor] is the only tensor of second order and K [the trace of the Ricci tensor] is the only invariant that can be constructed from only the $g^{\mu\nu}$ and its first and second order partial derivatives. . . .

This argument is, however, untenable because there are many other tensors of second order and many other invariants that can be constructed from the Riemann tensor; even if one requires linearity in the Ricci tensor, the crucial coefficient of the trace term remains undetermined by this argument. In the 1924 republication, he dropped this argument, replacing it with an outline of how to calculate the gravitational term [(10), p. 7]:

In order to determine the expression $[\sqrt{g}K]_{,\mu\nu}$ one first specializes the coordinate system in such a way that at the world point being considered all the $g^{\mu\nu}$ [the derivatives of the metric tensor] vanish. One finds in this way [our Eq. 2].

To summarize: Initially, Hilbert did not give the explicit form of the field equations; then, after Einstein had published his field equations, Hilbert claimed that no calculation is necessary; finally, he conceded that one is. Taken together, this sequence suggests that knowledge of Einstein's result may have been crucial to Hilbert's introduction of the trace term into his field equations.

In the light of this analysis of Hilbert's work, we can now better understand the exchange between Hilbert and Einstein in the crucial days of November 1915. On the 14th, Hilbert wrote to Einstein, inviting him to come to Göttingen 2 days later, when Hilbert intended to lecture on "my

axiomatic solution of your great problem." In a postscript, he added, "Insofar as I understand your new paper, the solution given by you is completely different from mine . . ." (18). Hilbert is referring to Einstein's communication of 4 November to the Prussian Academy of Sciences. On the 15th, Einstein replied (19), excusing himself from coming on grounds of being overworked, expressing great interest in Hilbert's work and asking for a copy of Hilbert's paper as soon as possible "to satisfy my impatience."

Hilbert must have sent the requested copy or a summary of his paper immediately because, on the 18th, Einstein replied, reacting sharply to Hilbert's claim of originality. Far from thanking him for sending his communication, as Fölsing claims, Einstein began his letter by denying the novelty of Hilbert's approach: "The system given by you agrees—as far as I can see—exactly with that which I found in recent weeks and submitted to the Academy" (20). In order to claim his priority, he explained to Hilbert that he had "considered the only possible generally covariant field equations three years earlier." He also insinuated that Hilbert had not even discussed the fundamental physical problems raised by these equations (20):

The difficulty was not to find generally covariant equations for the $g^{\mu\nu}$; this is easy with the help of the Riemann tensor. What was difficult instead was to recognize that these equations form a generalization, and, that is, a simple and natural generalization of Newton's law.

Einstein's claim is understandable. In his 4 November paper, he had announced with a flourish his return to the Riemann tensor as the appropriate starting point for a theory of gravitation (21). Although the theory in this paper is different from the version of Hilbert's theory that he saw, as well as from the version of the theory Einstein developed by the 18th, they are all based on the metric tensor and the only generally covariant tensor that can be built from it, the Riemann tensor, as their common foundation.

It was after this exchange with Hilbert that Einstein wrote a friend charging Hilbert with "nostrification." Einstein's letter of 18 November may have been the motive for a reputed apologetic letter (now lost) by Hilbert to Einstein [(7), p. 261] and Hilbert's handwritten note, added to the proofs of 6 December, supplementing his initial reference to the gravitational potentials $g_{\mu\nu}$ with the phrase "first introduced by Einstein" (Fig. 1).

In any case, by 20 December 1915, that is, before the appearance of Hilbert's final version, Einstein's anger had subsided to the

point that he offered to Hilbert a reconciliation (22):

There has been a certain resentment between us, the cause of which I do not want analyze any further. I have fought against the feeling of bitterness associated with it, and with complete success. I again think of you with undiminished kindness and I ask you to attempt the same with me. It is objectively a pity if two guys that have somewhat liberated themselves from this shabby world are not giving pleasure to each other.

In the printed version of his paper, Hilbert added a reference to Einstein's conclusive paper and a concession of the latter's priority: "The differential equations of gravitation that result are, as it seems to me, in agreement with the magnificent theory of general relativity established by Einstein in his later papers" [(3), p. 404]. If Hilbert had only altered the dateline to read "submitted on 20 November 1915, revised on [any date after 2 December 1915, the date of publication of Einstein's conclusive paper]," no later priority question could have arisen.

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cooperation in the archival work, especially in the dating of the central documents. They also thank P. Damerow, M. Janssen, U. Majer, D. Rowe, and T. Sauer for helpful discussions. We also thank Z. Rosenkranz and the Einstein Archives, The Hebrew University of Jerusalem, Israel, for permission to quote from Einstein's letters, and the Staats- und Universitätsbibliothek Göttingen (*Handschriftenabteilung*) for the kind permission to reproduce Fig. 1.

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Warming Early Mars with Carbon Dioxide Clouds That Scatter Infrared Radiation

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Geomorphic evidence that Mars was warm enough to support flowing water about 3.8 billion years ago presents a continuing enigma that cannot be explained by conventional greenhouse warming mechanisms. Model calculations show that the surface of early Mars could have been warmed through a scattering variant of the greenhouse effect, resulting from the ability of the carbon dioxide ice clouds to reflect the outgoing thermal radiation back to the surface. This process could also explain how Earth avoided an early irreversible glaciation and could extend the size of the habitable zone on extrasolar planets around stars.

It is most likely that the martian atmosphere 3.8 billion years ago was composed primarily of CO_2 , with a surface pressure ranging from a few hundred to several thousand millibars, and some H_2O (1). At that time, the solar luminosity was about 25% lower than it is at present. Under such conditions, calculations performed with a one-dimensional (1D) climate model by Kasting (2) showed that the atmospheric CO_2 should condense in the atmosphere for surface pressures larger than a few tens of millibars. Kasting found that the condensation of CO_2 decreases the atmospheric temperature lapse rate and reduces the magnitude of the greenhouse effect, making it impossible to warm the surface of Mars enough to allow the presence of fluid water together with a CO_2 - H_2O gaseous atmosphere. Several alternative mechanisms such as geothermal heating (3), an early more massive sun (4), or the greenhouse effect of methane (5) and ammonia (6) have been considered but none has provided a likely solution to the early Mars climate enigma (5).

Another consequence of the condensation of CO_2 is the formation of CO_2 ice clouds. Because they are perfect scatterers at solar radiation wavelengths, the CO_2 ice particles should raise the planetary albedo.

In the thermal infrared (IR), CO_2 ice is at least 500 times more transparent than water ice, except near $15\ \mu\text{m}$ where the ν_2 absorption band is located and above $90\ \mu\text{m}$ where two broad lattice vibration bands were measured (7). Thus, CO_2 ice clouds should not be able to contribute to an absorption-emission greenhouse effect as cirrus clouds on Earth do. On this basis, Kasting (2) estimated that CO_2 ice clouds should cool the planet through reflection of sunlight uncompensated by IR trapping.

We have studied the IR properties of the CO_2 ice clouds using a two-stream, hemispheric mean, source function code that allows for multiple scattering, absorption, and emission by atmospheric particles (8). The CO_2 ice particle single-scattering properties were obtained from the refractive index measured by Hansen (7), using Mie theory with a modified gamma size distribution of effective variance 0.1 (9). As expected by Kasting, a cloud composed of CO_2 ice particles smaller than a few micrometers should be almost transparent in the IR, except near $15\ \mu\text{m}$. However, larger particles can be expected in CO_2 ice clouds. Crystal size is determined by the time required for crystal growth versus the time it takes for the particles to fall out of a super-saturated layer (sedimentation). On Earth, despite the fact that the growth of water ice particles is limited by the diffusion of water vapor through air, particles $80\ \mu\text{m}$ or larger are often observed in cirrus ice clouds, and the observed radiative properties of Earth's cirrus clouds can be fit by assuming equiv-

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