Why Did Einstein Put So Much Emphasis on the Equivalence Principle?

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Einstein considered the discovery of the equivalence principle as "die glückichste Gedanke" in his life. Whether translated as "the happiest thought", "luckiest thought," or "the most fortunate thought," Einstein formulated the equivalence principle as the result of an epiphany he experienced in October 1907. He regarded the equivalence principle as the beginning step in adding gravitation to the special theory of relativity to create general relativity. Why? James Prescott Joule published a paper "On the Mechanical Value of Heat" in 1850 and started an avalanche of interest in the equivalence of different forms of energy. *Equivalence* was the hot new addition to the 19th century physics paradigm. Heat was also considered then as a mode of motion that led to the kinetic theory of gases, statistical analysis, Avogadro's number, the motion of atoms and molecules and Einstein's paper on Brownian motion. Einstein could not help but be aware of the significant meaning of equivalence to physics. An overly simplistic interpretation of the equivalence principle is that "gravitation is acceleration." But there is much more to this interpretation because the equivalence principle is at the heart of the derivation of the field equations of general relativity. Recognition of the overall importance of the equivalence principle leads to a dramatically new understanding of the general theory in the 21st century physics paradigm.

Introduction

Reconstruction of the events in Einstein's life is like reading a mystery story except that we think we know "who did it?" Although, we can't be too sure that Einstein did it because some people say that someone else discovered some of the things earlier than Einstein said that he did. But, what complicates things is that, in a number of cases, we don't know exactly when, where, what and how Einstein discovered what is credited to him. Support for these comments comes from Jürgen Neffe, author of **A Biography: Einstein**, in a chapter [1] "The Burden of Inheritance: Einstein Detectives in Action." **The Collected Papers of Einstein** consist of approximately 80,000 documents, copies of which have been zealously controlled by the Einstein Project Office at the California Institute of Technology in Pasadena, CA. The originals are in the Einstein Archives at the Hebrew University in Jerusalem, Israel. Other records of Einstein turn up periodically from various parts of the world. Einstein died in 1955. The first volume of **The Collected Papers** was not published until 1987. Other volumes have appeared irregularly over the years. Another decade or two may go by before full publication. Neffe devotes several pages to the people-issues of obtaining public access to the Einstein records. The following discussion of the equivalence principle is valid based upon the best available information.

My intent is to use as many of Einstein's own words as possible to discuss the background of the concept of the equivalence principle, to review various definitions by Einstein and others of the equivalence principle and to present my own understanding of how and why the equivalence principle was so significant to Einstein in deriving the field equations of general relativity. One of my lessons-learned is "Much is revealed about Einstein by matching the content of Einstein's personal communications with the content of his technical publications." Fortunately, the omissions in one are not usually repeated in the other.

Historic Origin of the Equivalence Principle

Concepts of equivalence principles were a "hot button" of interest to scientists in the latter half of the 19th century. James Preston Joule published [2] a paper "On the Mechanical Value of Heat" in 1850. Joule's paper describes an experiment that demonstrated the mechanical equivalence of heat and various forms of energy. Energy suddenly became a unifying concept for all sciences. As Ripley states [3], "Any good idea in science almost always appears to take on a life of its own. It grows vigorously in every possible direction. So it has been with the concept of energy. As soon as it was shown that heat could be regarded as a form of energy, the idea of energy was extended and generalized rapidly to include electrical, chemical and light and sound energy, each with its own conversion factor. All events in nature, biological as well as physical and chemical, were at last found to involve one process in common, that is, energy transformation." Equivalent forms of energy listed by Daniels and Alberty [4] that were known in the 19th century included mechanical energy, volume expansion energy and surface expansion

energy. Gravitational energy was added later. Efforts quickly expanded on the kinetic theory of gases, the motion of molecules and Avogadro's number. The work of Joule made possible the definition of the first law of thermodynamics which describes the equivalence between heat and work as forms of energy and the conservation of energy. Joule was recognized by naming the unit of energy after him.

Another part of the back story leading to the development of the equivalence principle has to be the "miracle year" of 1905 when Einstein had six technical papers published in **Annalen der Physik** (**AdP**). These papers are listed by Fölsing [5], who gives the titles in German and English of 296 of Einstein's publications from 1901 to 1955. Only four papers are usually cited for 1905 but all six published that year are given here.

- "On a Heuristic Viewpoint Concerning the Generation and Transformation of Light," **AdP**, 17, pp. 132-84 (1905). Description of the photoelectric effect. Received 18 March 1905. Einstein wrote [6] to his friend Conrad Habicht almost a year earlier in April 1904, "I have now found in a most simple way the relation between the size of elementary quanta of matter and the wavelength of radiation. "After publishing this paper, Einstein wrote [7] again in May 1905 to Habicht telling him about four papers, including the one just submitted, "The first deals with radiation and the energy properties of light and is very revolutionary, . . ."
- "On the Movement of Particles Suspended in Fluids at Rest, as Postulated by the Molecular Theory of Heat," **AdP**, 17, pp. 549-60 (1905). Explanation of Brownian motion. Received 11 May 1905. In the May letter to Habicht, Einstein commented on this paper that it "proves that bodies on the order of magnitude 1/1000 mm, suspended in liquids, must already perform an observable random motion."
- "On the Electrodynamics of Moving Bodies, **AdP**, 17, pp. 891-921 (1905). First paper on special relativity theory. Received 30 June 1905. In the May letter to Habicht, Einstein said "The . . . paper is only a rough draft at this point, and is an [sic, "on"] electrodynamics of moving bodies which employs a modification of space and time."
- "A New Determination of Molecular Dimensions," **AdP**, 19, pp. 289-305 (1906). A revision and supplement to the May 1905 paper. Received 19 August 1905. Einstein also commented to Habicht in the May letter, "This . . . paper is a determination of the true sizes of atoms."
- "Does the Inertia of a Body Depend on its Energy Content?" **AdP** 18, pp. 639-41. Supplement to SRT paper of May 1905 suggesting mass-energy equivalence. Received 27 September 1905. About the time he submitted this paper, Einstein wrote [8] another letter to Habicht and said, "One more consequence of the electrodynamics paper has crossed my mind. Namely, the relativity principle, together with Maxwell's equations, requires that mass be a direct measure of the energy contained in a body. Light carries mass with it."
- "On the Theory of the Brownian Motion," **AdP** 19, pp. 371-81 (1906). Statistical prediction of Brownian motion. Received 19 December 1905.

In addition to the above publications, Einstein had twenty-five reviews in **Beiblätter zu den Annalen der Physik, AdP**, 29 (1905). A Beiblatt (pronounced "by-blot" singular or "by-bletter" plural) is like a letter to the editor or supplement to papers. The Editor of **Annalen der Physik** at this time may have been Max Planck. Einstein also submitted his PhD thesis, "On a New Determination of Molecular Dimensions," on 30 April 1905 to be published by K. J. Wyss in Bern. Notice that Einstein wrote his August 1905 paper in **Annalen** on the same topic as his thesis. Einstein was very busy during 1905.

A couple more comments need to be added to assess what happened in 1907. Einstein knew about the work of Joule and others who were active in studying heat, equivalence of different forms of energy, and molecules during the latter half of the 19th century. Einstein's papers on heat, molecules and Brownian motion confirm that. Einstein refers [9] eight different times to the definition of the equivalence principle in **The Evolution of Physics**, which he co-authored with Leopold Infeld in 1938. Extensive references are also made in this book [10] to Joule and work on heat during the latter half of the 19th century.

With the above background in mind, let us look at the real time events during 1907 when Einstein supposedly first had the idea for the equivalence principle. Einstein started [11] work 23 June 1902 as a civil servant in the Patent Office in Bern, Switzerland. He had to evaluate the ideas of others. While still employed in the Patent Office in Bern, Einstein accepted an assignment [12] on 25 September 1907 to write a review article about special relativity for the *Yearbook of Radioactivity and Electronics*. Einstein wrote a letter [13] on 1 November to Johannes Stark, editor of the *Yearbook*, telling him that he had written part of the article, "I am now busy working on the second part in my scant free time….I certainly hope to be able to send you the manuscript at the end of the month." Although Einstein had already selected a title of "Relativity Principle and Gravitation" for the final pages of the review article, he was frustrated about how to add gravity to special relativity. Then a moment of inspiration after which Einstein wrote [14] this in the final pages of the *Yearbook* article, "In what follows we shall therefore assume the complete physical equivalence of a gravitational field and the corresponding acceleration of the reference frame. This assumption extends the principle of relativity to the case of uniformly accelerated motion of the reference frame." The completed manuscript "On the Relativity Principle and the Conclusions Drawn from It," was submitted [15] to Stark on 4 December 1907. These dates identify the window in which Einstein thought of the equivalence principle and began work on the general theory of relativity. A letter [16] on Christmas Eve 1907 to his friend Habicht confirms that Einstein was "busy on a relativity-theory examination of the law of gravitation, by which I hope to be able to explain the hitherto unexplained secular changes in the perihelium [sic] distance of Mercury."

The above paragraph presents the only real-time references known to me about the creation of the equivalence principle. Other descriptions of what happened in 1907 appeared in later years. Einstein extended his analysis to non-uniform acceleration and first referred to his hypothesis as the 'equivalence principle' in a 1912 publication [17] in **Annalen der Physik** (probably in the article on the "Theory of the Static Gravitational Field" cited by Fölsing [18]).

A few years later, Einstein was asked [19] in 1920 by R. W. Lawson of **Nature** to write a short article that was published in 1921 as "A Brief Outline of the Development of the Theory of Relativity" [20]. The paper that Einstein drafted was not so brief and had to be shortened for acceptance by

Nature. The longer draft [21] contains the often quoted phrase by Einstein explaining his feelings about the epiphany he had when he discovered the equivalence principle "[Es war die] glücklichste Gedanke meines Lebens." Biographers like to use this phrase as a chapter title. Whether translated as "It was the happiest thought of my life," the "luckiest thought," or the "most fortunate thought," it was a moment to remember. This draft article is quoted in more detail relative to the equivalence principle by Pais [22].

One other explanation [23] of what happened in 1907 entered the record in Kyoto, Japan on 14 December 1922 in an off-the-cuff lecture by Einstein "How I Created the Theory of Relativity." This is what Einstein said then [24] about an October day fifteen years before. "I was sitting in a chair in the patent office at Bern when all of a sudden a thought occurred to me: 'If a person falls freely he will not feel his own weight.' I was startled. This simple thought made a deep impression on me. It impelled me toward a theory of gravitation."

Awareness of all the above historical background details motivated me to describe what may have actually happened to inspire Einstein to think of the equivalence principle. Let us create a legend.

Sometime during October 1907, probably the second or third week, Einstein was on the job and was sitting at his desk with a new batch of patents to review. Before he started reading one of the patents, Einstein leaned back in his chair, pushed some papers out of the way and swung his feet upon his desk top. He pondered the patent and leaned back a little more—and a little more, until he felt the feeling of exotic motion when experiencing free fall. He had a momentary sense of zero gravity and then the sudden panic of trying to grab hold of something to brace his fall. As Einstein sprawled on the floor, he made a quick check of his body for damage. Then, two magnificent, unexpected, and exhilarating thoughts welled up in him. "Gravitation is acceleration. Gravitational mass is the same as inertial mass—I fell on my mass!" He laughed out loud and looked around to see if anyone saw what happened. He thought to himself, "Newton had his apple. I have my chair." And, he laughed again, got up, put his inspirational chair into an upright position, sat down and started to write."

The events I just described may or may not have happened. As far as I know, no one else has described Einstein's inspirational moment for discovery of the equivalence principle in this manner. Some accounts talk about a painter who fell off a nearby building in Bern. However, I know of no other cause-and-effect event happening at an office desk that could have realistically given Einstein such an epiphany as he described. Reread Einstein's words three paragraphs above about when he was sitting at his desk: "sitting in a chair," "all of a sudden," "if a person falls freely," "startled," "deep impression," "impelled." Archimedes had his bath, Galileo had his leaning tower, Newton had his apple, and Einstein had his chair.

In addition to Einstein many others have discussed the equivalence principle. Two excellent assessments of progress in understanding gravitation are **General Relativity: An Einstein Centenary Survey** [25] published in 1979 and **300 Years of Gravitation** [26] published in 1987. Both were co-edited by Stephen Hawking and Werner Israel.

Varieties of Equivalence Principles

Einstein applied various versions of the equivalence principle in deriving the field equations of general relativity. Based upon the sources mentioned so far, plus three of his papers, Einstein probably reasoned in the following manner starting with Newton's first and second laws of motion [27].

- Newton's First Law: Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it. Special relativity theory obeys this law.
- Newton's Second Law: The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed. The general theory corresponds to this law. Einstein wanted his field equations to converge on the Newton gravitational force at low velocities, low masses and large separations.
- The inertial mass in Newton's first law is equivalent to the acceleration mass in Newton's second law.
- The inertial mass and the acceleration mass are each equivalent to the gravitational mass in Newton's inverse square law of universal gravitation.
- Inertial mass is equivalent to gravitational mass; gravitation is acceleration. These two statements represent the earliest form of the Einstein equivalence principles. Einstein used this new awareness to begin writing the second part of his 1907 Yearbook survey article.
- Einstein concluded that all forms of mass were equivalent, including the mass in Einstein's mass-energy equation relationship. This conclusion was put to use in deriving the field equations.
- Since all forms of energy are equivalent based upon Joule's work, then gravitational energy can be treated the same as any other form of energy.
- Einstein concluded that the gravitational potential energy is equivalent to mass-energy equivalence. This conclusion was the basis of starting the derivation of the field equations of general relativity and is key to understanding its limits.

Einstein's Use of Equivalence Principles

Fig. 1 shows the static stage of Einstein's two-stage derivation of the field equations of general relativity. The derivation of general relativity starts with the Newton gravitational force in Step 1. Step 2 indicates the application of the Einstein equivalence principle by setting the Newton gravitational potential energy equal to the mass-energy equivalence (last bullet above). Step 3 results from the assumptions inherent in Step 2. A number of options exist after Step 3. Einstein chose to go directly to Step 4.

Step 4 is the result used as a basis for predicting the bending of light in a gravitational field as described in [28] Einstein's 1911 paper "On the Influence of Gravitation on the Propagation of Light." More details on the derivation in Fig. 1 were presented in the 14th Natural Philosophy Alliance Conference (NPA) in 2007 [29].

After Step 4 Einstein began work in 1912 on the left-side of the field equations to derive the relationships that defined

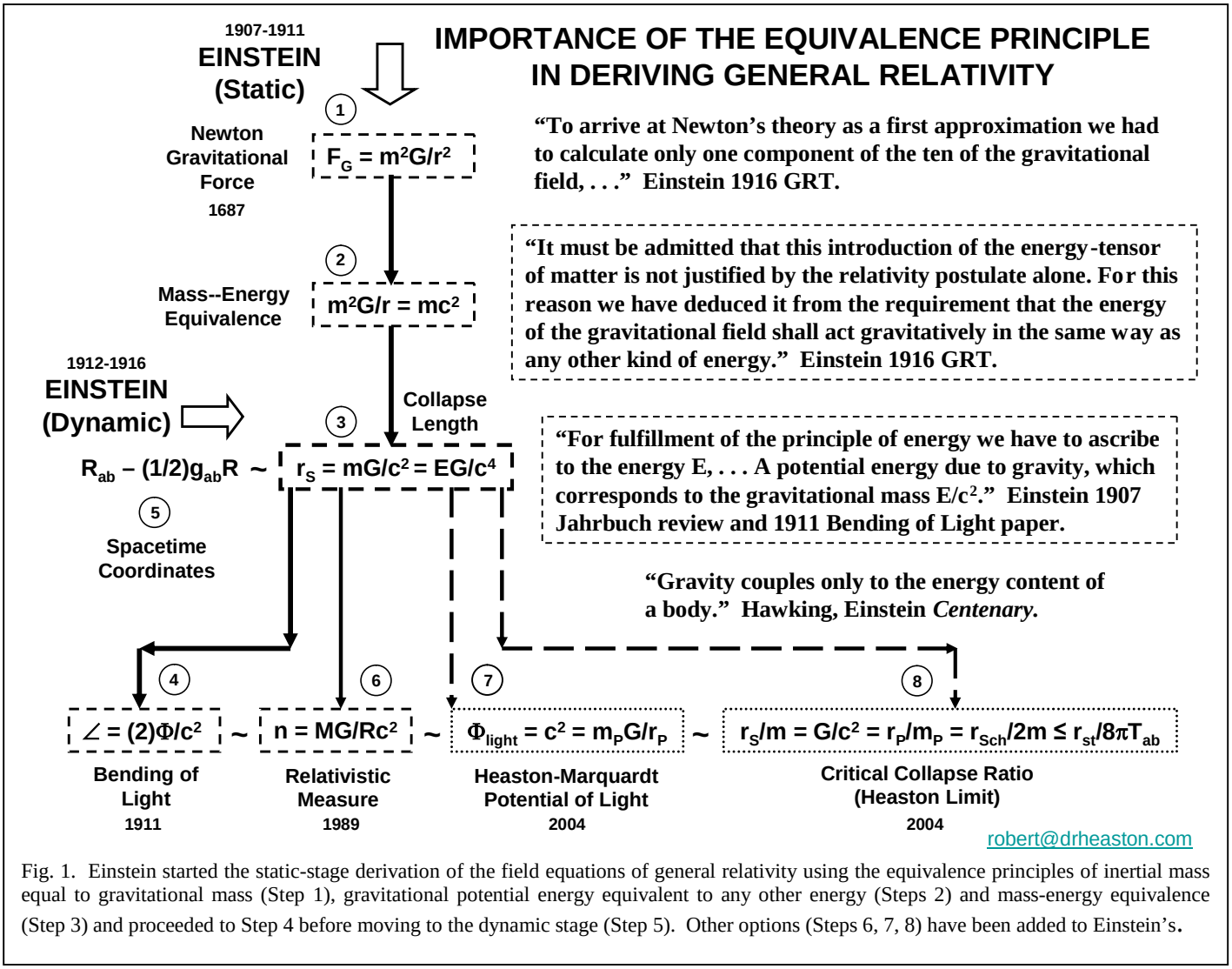

Fig. 1. Einstein started the static-stage derivation of the field equations of general relativity using the equivalence principles of inertial mass equal to gravitational mass (Step 1), gravitational potential energy equivalent to any other energy (Steps 2) and mass-energy equivalence (Step 3) and proceeded to Step 4 before moving to the dynamic stage (Step 5). Other options (Steps 6, 7, 8) have been added to Einstein's.

gravity as the curvature of spacetime. In this process, Einstein absorbed Steps 1, 2 and 3 into his derivation that included the mass-momentum-energy density functions representing the right-side of the field equations without explaining Steps 1, 2 and 3 again. The right-side would have been impossible to derive without going through Steps 1, 2 and 3.

My primary objective here is to show how the equivalence principle was important to get to Step 4. My secondary objective is, if Step 4 is allowed, then Step 3 is essential and Steps 5, 6 and 7 must also be permitted. These last three steps will be explained in another paper [30] given at this conference "A Third Alternative to the Generation of Energy by Fission and Fusion."

Conclusions

The record leaves no doubt that Einstein had an epiphany during October 1907. Reconstruction to determine when this event happened and what occurred required a lot of digging. Six reasons for Einstein to exult over what happened are listed below. These six reasons answer the title question of this paper.

1. The equivalence principle answered a need for a theme for the second part of the 1907 Yearbook review article.
2. The equivalence principle pointed a way to add gravitation to the special relativity theory.
3. The equivalence principle suggested the beginning steps for the derivation of general relativity theory.
4. The equivalence principle, as defined by Einstein, guaranteed convergence on the Newtonian gravitational force.
5. The equivalence principle resulted in a model of the mass-energy density tensor component of general relativity theory.
6. The equivalence principle provided an overall template for the field equations of a general relativity theory.

Many different definitions of an equivalence principle exist. Anyone who states in a paper that "the equivalence principle was used" should state what form of principle was used, how it was applied and what was achieved in its use.

An unexpected consequence of trying to understand Einstein's formulation of the equivalence principle is the possibility that a door has been opened and general relativity may have a new life in the 21st century physics paradigm.

References and Notes

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[6] W. Isaacson. **Einstein: His Life and Universe**, New York: Simon & Schuster, p. 97 (2007). Quote from 1904 Einstein letter to Habicht about writing a paper on the photoelectric effect.

[7] Ibid., p. 93. Quote from May 1905 Einstein letter to Habicht about four papers Einstein was writing, including SRT.

[8] Ibid., pp. 137-138. Another Einstein letter in September 1905 to Habicht where Einstein said that mass is energy.

[9] A. Einstein and L. Infeld. **The Evolution of Physics: The Growth of Ideas from Early Concepts in Relativity and Quanta**, New York: Simon & Schuster, pp. 33, 34, 35, 215, 217, 221, 222 and 245 (1961). Eight different references to the equivalence principle.

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[12] A. Pais. "Subtle is the Lord . . . ': **The Science and the Life of Albert Einstein**, Oxford: Oxford University Press, p. 179 (1982). Einstein accepts assignment to write yearbook review of relativity on 25 September 1907.

[13] Fölsing, p. 305. Einstein writes letter on 1 November 1907 saying that the SRT part of yearbook review was completed.

[14] Pais, p. 180. Einstein describes plans on deriving GRT on the last page of the yearbook review article.

[15] Fölsing, pp. 306, 827. On 4 December 1907, Einstein submits his review article to the yearbook for publication

[16] Ibid., p. 306. Einstein writes 24 December 1907 letter to Habicht saying that he has begun derivation of GRT.

[17] Pais, p. 180. Equivalence principle first described by name in 1912 publication.

[18] Fölsing, p. 829. Title of publication where the equivalence principle was first mentioned.

[19] Pais, p. 179. This and next three references needed to pin-point origin of the "the luckiest thought" comment by Einstein.

[20] Fölsing, p. 836]

[21] Isaacson, p. 145.

[22] Pais, p. 178.

[23] A. Einstein. "How I Constructed the Theory of Relativity," Translated by Masahiro Morikawa from the text recorded in Japanese by Jun Ishiwara, **Association of Asia Pacific Physical Societies (AAPPS) Bulletin**, Vol. 15, No. 2, pp. 17-19 (April 2005). Einstein recalls events of 1907 in talk in Japan on 14 December 1922.

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