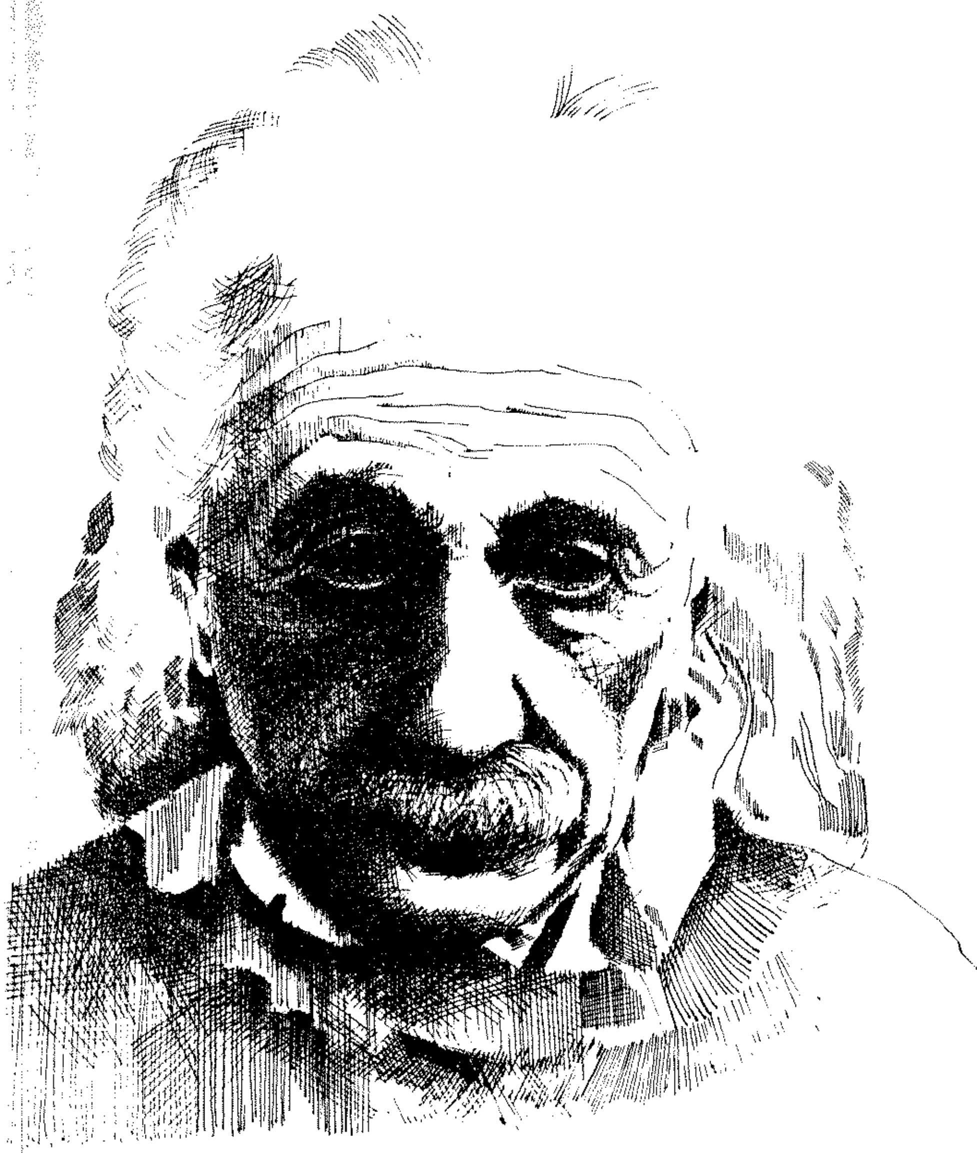

Albert Einstein's Theory of General Relativity

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May this hour of grateful remembrance serve to strengthen within us the love and esteem in which we hold the treasures of our culture, gained in such bitter struggle. Our fight to preserve those treasures against the present powers of darkness and barbarism cannot then but carry the day.

A. Einstein, New York, 1935

This volume is humbly dedicated to the memory of my parents and the six million victims of the holocaust. May they rest in peace.

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bridge-representation of the electric corpuscle. The simplest solution of this kind is that for an electrical particle without gravitational mass.

So long as the considerable mathematical difficulties concerned with the solution of the several-bridge-problem are not overcome, nothing can be said concerning the usefulness of the theory from the physicist's point of view. However, it constitutes, as a matter of fact, the first attempt toward the consistent elaboration of a field theory which presents a possibility of explaining the properties of matter. In favor of this attempt one should also add that it is based on the simplest possible relativistic field equations known today.

MERCER STREET AND OTHER MEMORIES

Gathered by

JOHN ARCHIBALD WHEELER

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The famous 1950 film *Rashomon* recounts a dramatic episode three times over in the very different versions perceived by three of those who took part. The account of a May 16, 1953, visit to Einstein given here differs in that there are four versions supplied respectively by John Wheeler, Marcel Wellner, Arthur Komar and O. W. Greenberg. The editor (J. A. W.) expresses his appreciation to them for the permission to quote them, and to the Albert Einstein Estate for permission to quote brief passages from Einstein's writings.

MERCER STREET AND OTHER MEMORIES

JOHN ARCHIBALD WHEELER

My first chance to see and hear Albert Einstein came one afternoon in the academic year 1933–34. I was in my first year of postdoctoral work with Gregory Breit in New York. He told me that there would be a quiet, small, unannounced seminar by Einstein that afternoon. We took the train to Princeton and walked to Fine Hall. Unified field theory was to be the topic, it became clear, when Einstein entered the room and began to speak. His English, though a little accented, was beautifully clear and slow. His delivery was spontaneous and serious with every now and then a touch of humor. I was not familiar with his subjects at that time but I could sense that he had his doubts about the particular version of unified field theory he was then discussing. I had been accustomed before this to seminars in physics where equations were taken up one at a time or, if I may say so, dealt with as in retail trade. Here for the first time I saw equations dealt with wholesale. One counted the number of unknowns and the number of supplementary conditions and compared them with the number of equations and the number of coordinate degrees of freedom. The idea was not to solve the equations but rather to decide whether they possessed a solution and whether it was unique. It was clear on this first encounter that Einstein was following very much his own line, independent of the interest in nuclear physics then at high tide in the United States.

In 1938 I moved to Princeton and at infrequent intervals called on Einstein at his house at 112 Mercer Street, climbing the stairs to his second floor study that looked out on the Graduate College. Once discussing with him my hopes some day to understand radiation damping in terms of the interaction between the source and the absorber, he told me about his debate with W. Ritz.[1] The two men joined to write up their contrasting points of view in a joint paper. In it Ritz argued that the elementary interaction is responsible for the irreversibility. In contrast Einstein favored the view that elementary interactions are time symmetric and that any irreversibility is caused by asymmetry in time of the initial conditions. He also made reference to a fascinating paper of Tetrode[2] on the same question.

Especially vivid in my mind is a call I made in 1941 to explain the "sum over histories" approach to quantum mechanics then being developed by Richard Feynman,[3] whom I was fortunate enough to have as a graduate student. I had gone to see Einstein with the hope of persuading him of the naturalness of quantum theory when seen in this new light, connected so closely and so beautifully with the variation principle of classical mechanics. He listened to me patiently for twenty minutes until I finished. At the end he repeated that familiar remark of his, "I still cannot believe that the good Lord plays dice."[4] And then he went on to add again in his beautifully slow, clear, well-modulated and humorous way, "Of course I may be wrong; but perhaps I have earned the right to make my mistakes."

In the fall of 1952 I gave for the first time the course in relativity, general and special, from which I was to learn so much from my students over the years. On May 16, 1953, not quite two years before he died, Einstein was kind enough to invite me to bring the eight to ten students in the course around to his house for tea. [The recollections kindly provided by three of them follow: Arthur Komar, Marcel Wellner and O. W. Greenberg.] Margot Einstein and Helen Dukas served tea as we sat around the dining room table. The students asked questions about everything from the nature of electricity and unified field theory to the expanding universe and his position on quantum theory, and Einstein responded at length and fascinatingly. Finally one student outdid the others in the boldness of his question: "Professor Einstein, what will become of this house when you are no longer living?" Einstein's face took on that humorous smile and again he spoke in that beautiful, slow, slightly accented English that could have been converted immediately into printer's type, "This house will never become a place of pilgrimage where the pilgrims come to look at the bones of the saint." And so it is today. The tourist buses drive up. The pilgrims climb out to photograph the house—but they don't go in.

A further encounter was my last. We persuaded him to give a seminar to a restricted group. In it the quantum was a central topic. No one can forget how he expressed his discomfort about the role of the observer. "When a person such as a mouse observes the universe, does that change the state of the universe?"

In all the history of human thought there is no greater dialogue than that which took place over the years between Niels Bohr and Albert Einstein about the meaning of the quantum. Their discussion has already been depicted in sculpture and surely will be described some day in pictures and words. Nobody can forget Einstein's letter to the young Bohr when first he met him: "I am studying your great works and—when I get stuck anywhere—now have the pleasure of seeing your friendly young face before me smiling and explaining."[5] There is no greater monument to the dialogue than Bohr's summary of it in Paul Arthur Schilpp, editor, *Albert Einstein: Philosopher-Scientist.*[6]

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ARTHUR KOMAR'S REMEMBRANCES

There were about eight of us. We sat down and had tea. Miss Dukas brought the tea. Einstein said he was so pleased to have some contact with young people. John Wheeler asked him about the Einstein-Rosen bridge. Why did he first introduce it, then drop it? Einstein said he originally thought of it as a unique structure reaching across two nearly flat sheets. However, when he realized it was not unique, the bridge seemed to him unwieldy, unattractive, and offering too many possibilities. It was not clear what to do with them all.

Arthur Komar's version of the May 16, 1953, visit of Class in Relativity to Einstein's residence at 112 Mercer Street, Princeton, as told to John A. Wheeler, August 8, 1977.

Arthur Komar asked what he thought of the idea of Eddington for getting the dimensionless constants. Einstein replied that he was much interested in finding a theory or an understanding of the dimensionless constants; but he felt that there was no solution of real interest available at that time. Komar did not remember questions about the expanding universe or gravitational radiation or the nature of electricity. He did recall that vivid phrase at the end "This house will never become a place of pilgrimage where the pilgrims come to look at the bones of the saint." The whole encounter was in English. Komar also remembered Einstein's coming to Palmer Physical Laboratory and giving a talk containing two striking comments: (1) The laws of physics should be simple. Someone in the audience asked, "But what if they are not simple?" "Then I would not be interested in them." (2) Einstein was asked why he rejected quantum mechanics. He said he could not accept the concept of a priori probability. Someone in the audience said, "But you were the one who introduced a priori probability, in the A and B coefficients." "Yes, I know that and have regretted it ever since; but when one is doing physics one should not let one's left hand know what one's right hand is doing." At the end of this lecture he sat down, leaned back, sighed and said, "This is my last examination."

EXCERPTS FROM A 10 SEPTEMBER 1977 LETTER FROM MARCEL WELLNER TO JOHN A. WHEELER

"My memory of our meeting with Einstein [May 16, 1953] is still fairly vivid. I seem to recall that most of us were too intimidated to ask him very much, and you had to be our spokesman. This was in spite of the fact that we were pretty well prepared. I am enclosing [see below] a copy of a problem assignment which you gave us shortly before that, and which reflects our preoccupations during the course you were teaching at the time. Your questions 1 and 2 seem particularly relevant here.

"At Einstein's you asked on our behalf what were his thoughts on Mach's principle. This must have been somewhat removed from his own concerns at the time, because you had to repeat the word 'Mach' in its German pronunciation to clarify the question. (As you can see, my memory is mainly of an auditory kind.)

"His answer was somewhat disappointing—at least to me. He said he no longer held to his earlier views about Mach's principle, and that perhaps there wasn't in nature anything corresponding to Mach's principle after all."

PROBLEMS: [For class in relativity in May 1953, a few days before the hoped-for visit with Einstein.]

1. Present Mach's principle in a form as eloquent and clear as possible, and independent of any reference to Einstein's theory. At the end of the presen-

tation, give a brief summary of the points still to be investigated in order that this principle should have a satisfactory and logically sound mathematical formulation.

2. List three questions that you would like to put up to Einstein, with a one paragraph elaboration of each.
3. Treat the problem of an infinitesimal test particle started from rest from an arbitrary point in the Schwarzschild field.
4. Derive the Schwarzschild values for a and b in $(ds)^2 = -a\,(dr)^2 - r^2[(d\theta)^2 + (\sin\theta\, d\psi)^2] + b(dt)^2$ from the variation principle $\delta \int\int\int\int R d(\text{vol}) = 0$.

MERCER STREET

A spring afternoon,
A line of nine walk through the town,
A musty house, the shutters drawn,
A sage lives within.

His key turned the lock
For twenty years, to unify
Electric field, magnetic field,
Space-time, matter, too.

A calm beyond time,
A humble man, received his guests.
To talk, to feel the breath of youth,
To hand them the key.

The day turned to dusk.
The parting time. Advice was sought
For these young men who start the path
He lost long ago.

He shrugged, scratched his head.
Discomforted, at sea, he sent
Them out with "Who am I to say?"
Cool air cleared their heads.

Oscar Wallace Greenberg

EINSTEIN'S LAST LECTURE

Quantum theory: In which sense is it not final? "Classical" quantum theory—founded on Hamiltonian equations, similar to electrodynamics founded on Maxwell equations. How did I become a heretic? Radiation raises system to a higher state. One can weaken the field indefinitely. The system is raised more and more rarely to the higher state. The probability becomes infinitely small to produce a finite effect. One cannot of course formulate this situation satisfactorily in any mathematical scheme. Therefore, one is led to a probabilistic description. One finds himself saying that probability is a definite part of reality. It is an advantage that the law of Coulomb can be used in the new scheme, by translation from classical theory. I am a heretic. If radiation causes jumps, it must have a granular character like matter.

What is really the meaning of ψ? Can't believe that the state in quantum theory provides a complete representation of the physical situation. Consider a sphere 1 mm in diameter. One can see it with the eye. It can go to and fro between two planes, ideally elastic. One can forget the internal coordinates of the sphere. Consider a state of fixed energy (Fig. 1). If one neglects the fine structure, all places have the same probability. More accurately, there are some places where the thing can never be. This is contrary to the ordinary Newtonian idea of motion. There is no question that this is true; it certainly corresponds to reality. Fourier analysis shows there is a probability of 1/2 for $v = v_o$, and 1/2 for $v = -v_o$.

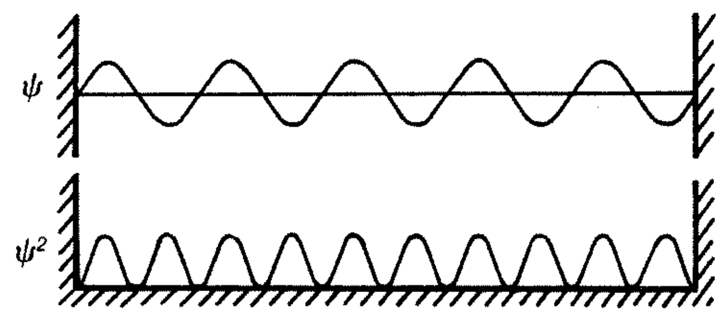

Fig. 1

It is difficult to believe that this description is complete. It seems to make the world quite nebulous unless somebody, like a mouse, is looking at it. The problem is to understand that one can observe the particle with a lantern.

The scheme is of very great practical value as long as we have nothing better, and makes good use of the concepts such as mass and change with

From Einstein's lecture at the J. A. Wheeler relativity seminar, introduced by O. W. Greenberg, in Room 307, Palmer Physical Laboratory, Princeton University, April 14, 1954. [Notes taken by J. A. W. at the time.]

which physics started in the earliest days. But one has to mistrust it if one believes in a deeper scheme.

The Maxwellian scheme is marvellously effective in explaining many things, particularly macroscopic. But it runs into trouble on radiation. Fluctuations are bigger on Planck's law than they are on Maxwellian theory.

I knew in constructing special relativity that it was not complete. So is everything that we do in our time: with one hand we believe; with the other, we doubt. I once thought temperature a basic concept. I feel the same way about Maxwellian theory. But I am now convinced there is no cheap way out. If there are too many hypothetical elements one cannot believe one is on the right track. Thus I came to logical simplicity, a desperate [man's] way to get on the right track. But one event in my life convinced me of the usefulness of logical simplicity. That was general relativity.

It can be looked at as a theory which makes us independent of the inertial system. The concept of inertial system was regarded by the founder himself, and his scientific enemy, Huygens, and Leibniz, as exceedingly unclear. For Galileo, acceleration is the fundamental concept on which mechanics is founded. But what is acceleration? Newton invented the infinitesimal calculus. But this really doesn't provide an answer. There are coordinate systems that are inertial and others that are not. A coordinate system is satisfactory if in it the equations of motion hold. In classical theory there are three independent concepts: space, time, material points. The behavior of material points is determined by the inertial system. But this is like God Almighty, unaffected by anything else. Newton recognized very clearly it was very hard to regard space as something absolute. This is not the direct way I found the theory of gravitation. The real way is a very strange story.

I had to write a paper about the content of special relativity. Then I came to the question how to handle gravity. The object falls with a different acceleration if it is moving than if it is not moving (Fig. 2). Thus a gas falls with another acceleration if heated than if not heated. I felt this is not true. Came out that acceleration is independent of *quality* of matter: pendulum experiments.

Change coordinate system? Then change acceleration. Then I came to a real understanding of the equivalence of gravitational and inertial mass. *No* inertial system can be preferred. That was not so clear to me at that time. But Mach had the same idea, not the relation of gravitational and inertial mass, but that "inertial system" was a very vicious concept. Inertia come from the presence of other bodies? How possible? *Relative* acceleration and against this a resistance. Quite a nice idea. But if you give up space, you have an enormous number of distances, and unhandy consistency relations. Mach not aware of time concept. Great thing that Mach, centuries after Newton, felt that there was something important about this concept of avoiding an inertial system. Need absolute covariance.

Not yet so clear in Riemann's concept of space. His curvature is abso-

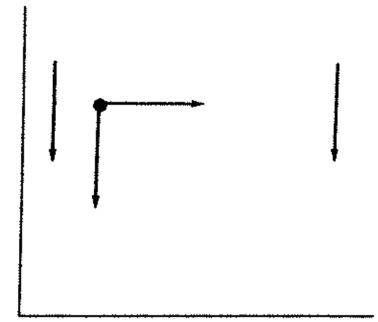

Fig. 2

lutely covariant. But this was not so clear at the time this work was presented by Riemann and his successors. The first to see this clearly was Levi-Civita: absolute parallelism and a way to differentiate. Recognized that possibility to avoid inertial system depended on existence of a Γ-field that described parallelism in the infinitesimally small. This was a great advance. It made it possible to see how to generalize relativity to include electromagnetism.

The representation of matter by a tensor was only a fill-in to make it possible to do something temporarily, a wooden nose in a snow man. The theory wasn't complete, because we know the world is not limited to gravitation. After decades I came to the idea to generalize by using unsymmetric g_{ij}'s, the method of logical consistency gone mad. I was very conscious of this objection. Γ is a field. Without this there is no hope to express things in general relativity.

Present quantum theory based on special relativity is horribly complicated. For most people special relativity, electromagnetism and gravitation are unimportant, to be added in at the end after everything else has been done. On the contrary, we have to take them into account from the beginning. Otherwise it is as if one did a classical problem and put in the law of conservation of energy at the end. Expect to describe a system only by quantum numbers. There is much reasonable in this. But a field theory seems to present us with an infinite number of quantum numbers. There is much reason to be attracted to a theory with no space, no time. But nobody has an idea how to build it up. Of course, to quantize space and time is a childish idea. This is my excuse for feeling so strongly. It is pedagogic to insist that if one has a field theory, one must demand solutions without singularity. If a singularity is allowed, there are too many arbitrary assumptions, and too much arbitrariness.

QUESTIONS

Greenberg: Do you have a different interpretation of deBroglie waves?

Einstein: I consider them almost comparable in reality to light waves, but not quite. There are so many fields as there are masses; and then the trouble of higher . . . [word missed].

Callaway: The equivalence principle says it is reasonable to absorb *gravitation* in the metric. But no such principle is known for electromagnetic theory.

Einstein: I believe that the concept of motion has no place in a unified theory; that "geodesic lines" are only a provisory concept, a stopgap. Also it is against the whole idea of quantum theory.

Greenberg: Is there anything in gravitation theory corresponding to radiation?

Einstein: This is a headache. Why not expect also gravitational quanta? But this is hard to include in field theory. Perhaps this is an objection to any field theory that has to do with gravitation. Electromagnetic waves can be put into a container, but gravitational waves cannot—there are two signs of charge for the one; only one for the other. Thus there is a difference in kind between the two theories. This gives the feeling that gravitation is not more true than any classical theory. There is an infinity of constants in a field theory. Only way to overcome: if the condition of nonexistence of singularities in a very unenigmatic way fixed up quantum numbers.

Carlson: What do you think of Bohm's theory?

Einstein: It is clever, but I don't believe it. It is outrageous to believe that the particle between walls does not move.

Komar: Why is unified theory simpler than projective theory?

Einstein: The most basic thing in relativity is the replacement of a field by something like a Γ. In gravitation we have to symmetrize. So we can think unified theory is a simplification of gravitation theory. But gravitation theory is a field theory, and may have difficulties.

Callaway: What do you think of Mach's principle?

Einstein: Mach assumes matter may be permanent. Therefore, why separate the rest of the field from the gravitational field? We have a satisfactory description in conformity with Mach's principle if we have a theory without boundary conditions. I once thought to take the universe roughly static and closed in space. Then came the cosmological λ. But it was a sin against mathematical simplicity. If the world is expanding, it is hopeless. Time is essential. A boundary is unthinkable. Your question is related to the role of matter.

Mozeley: Must a field theory be deterministic?

Einstein: [first few words missed] It is the negative part of determinism that probability should not intervene, because it is not a quality of the system.

THE BLACK HOLE: AN IMAGINARY CONVERSATION WITH ALBERT EINSTEIN

JOHN ARCHIBALD WHEELER

Center for Theoretical Physics, Department of Physics, University of Texas, Austin, Texas

Wheeler: Professor Einstein? Professor Einstein! Oh how wonderful to see you here!

Einstein: Yes, I thought I would surprise you, Mr. Wheeler. But you know I like the sea shore and the waves as much as you do.

Wheeler: But the biggest miracle of all is not our picking the same prospect over sea and distant islands; it is that you should be here at all. What wonderful fortune!

Einstein: Yes, I thought you would be surprised. I am too. Could it have anything to do with those old stories that one is permitted to come back to Earth again for a single hour on one's hundredth birthday? Do you remember Niels Bohr's story about why hang up a horseshoe over your desk?

Wheeler: No, I don't think I heard that one.

Einstein: He used to say, "I don't believe in miracles at all—and especially not in horseshoes. But you know that people who do tell me that it doesn't hurt your luck if you don't believe."[1] That must be the general idea of how come I am here now.

Wheeler: Less than a hour left and that I rejoice in all this beauty. No wonder you don't want to ask questions but only look and smile and close your eyes and look again. But while you look could I ask you some questions? So many colleagues have regretted with me all the questions, great and important questions, that we failed to ask you before you left our midst.

Einstein: But yes. Still you must not consider me an expert. When I was young I made so much trouble for authority that in later life, in punishment, the Lord made me an authority myself[2]; but I am no more.

Wheeler: Why did you not say more about what we today call the "black hole"?

Einstein: Yes, I know what you mean: a completely collapsed star. It was not so easy to discuss such questions in my time. What after all is one to take for the equation of state of the matter of the star? That is not so easy.

Wheeler: Then I'm sure you'll rejoice in the theorems of today that a sufficiently massive collection of cold matter has no escape from gravitational collapse.

Einstein: Of course it is much simpler to stay away from all special assumptions about the relation between density and pressure. That is why in my 1939 paper[3] I considered a collection of well-separated point masses in orbit about