Einstein's Legacy

OLLI lectures Fall 2015 Horst D Wahl

Lecture 6 4 Nov 2015

Outline of 6th class

Recap

- □ More on special relativity
 - Four-vectors
 - Minkowski metric
- Special Relativity, consequences, sequel
 - Consequences of Special Relativity
 - Einstein and the atomic bomb
- □ AE Life Milestones 1905 1920
- General Relativity
 - Extension of SR to accelerated frames
 - Equivalence principle
 - Light deflection by stars
 - GR field equations
 - cosmology
- □ AE milestones 1920 1955

Recap

Relativity

Physics background

- o Geometry of space
- o Reference frames
- o Galilean relativity
- o Speed of light
- o Electrodynamics
- o Luminiferous aether
- o Michelson-Morley experiment
- o Conundrum of Newtonian physics
- o Attempts of resolution

Einstein's special relativity

- o Relativity principle
- o Constancy of speed of light
- o Lorentz transformation
- o Consequences:
 - Simultaneity, time dilation, length contraction, equivalence of mass and energy

Response, Sequel

- o Reaction, sequel
- o Spacetime
- o Einstein's sequel
- o Consequences of Special Relativity

More on special relativity

□ Four-vectors

Energy-momentum Length of four-vectors □ Metric of 4-dimensional spacetime relativistic energy and momentum □ Consequences of SR Equivalence of mass and energy Time dilation, evidence Length contraction



Four-vectors

special relativity implies that we live in a fourdimensional spacetime

 > vectors in 3 dimensional space become "four-vectors", acquiring a "time-like" component

Position in spacetime is a "four-vector"

$$x = (ct, \vec{x}) = (x_o, x_1, x_2, x_3)$$

• Momentum \Rightarrow energy-momentum four-vector

$$p = (E, c\vec{p}) = (p_o, p_1, p_2, p_3)$$

Momentum in relativity

□ Special relativity:

• due to relativistic rule of velocity addition, it turns out that momentum as defined in Newtonian mechanics $\vec{p} = m\vec{v}$ is not conserved

Relativistic generalization of momentum

$$\vec{p} = m\gamma \vec{v}$$

More on four-vectors

□ four-vectors:

- time and position $x = (ct, \vec{x}) = (x_o, x_1, x_2, x_3) = x_\mu, \mu = 0,...,3$
- energy and momentum

$$p = (E, c\vec{p}) = (p_o, p_1, p_2, p_3) = p_\mu, \mu = 0, ..., 3 = mc^2 \gamma(1, \frac{\vec{v}}{c}) = mc^2(\gamma, \vec{\beta})$$

- 4-dimensional spacetime: metric different from "normal" 3dimensional space ⇒ new prescription for calculation of length of a vector
- (Length of four-vector)² = (time component)² (length of space vector)²
- "length" of four-vector is invariant under Lorentz transformation
- energy-momentum 4-vector: "length" = mc²
- equivalence of mass and energy: mass is a form of energy, mass energy can be converted into kinetic energy and vice versa

Length of vectors

vector A specified by

Length and direction

o (one angle in plane, 2 angles in 3-dimensional space)

Components

o = projections of vector on suitable chosen coordinate axes

- o in plane (2-dimensional space): 2 components A_x , A_y (or A_1 , A_2)
- o in 3-dimensional space: 3 components A_x , A_y , A_z (or A_1 , A_2 , A_3)

From components get length with Pythagorean theorem :

$$(length(\vec{A}))^2 = \vec{A}^2 = A_1A_1 + A_2A_2 + A_3A_3$$

- Prescription on how to get length² depends on "metric" of space; in our familiar "Euclidian" space it is the sum of squares of the components as shown above
- In 4-dimensional spacetime, the prescription for length is different – different metric

Length of vectors vs rotations

effect of rotation on vectors:

- in our "normal" 3-dimensional space, components of vectors change when vector is rotated (or coordinate system is rotated)
- But length of vector does not change it is "invariant" under rotations
- Lorentz transformation
 - can be interpreted as a rotation in 4-dimensional spacetime
 - What is the length that is invariant under this rotation?
 - New metric for 4-dimensional spacetime allows definition of "length" which is invariant under Lorentz transformation – called a "Lorentz-invariant"

Metric Tensor

 $\hfill\square$ Metric tensor $g_{\mu\nu}$ describes geometry of spacetime via the

• (infinitesimal) line element

$$(ds)^2 = \sum_{\mu\nu} g_{\mu\nu} dx_{\mu} dx_{\nu}$$

□ Metric for "ordinary" 3D (Euclidean) space

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(dl)^{2} = (dx)^{2} + (dy)^{2} + (dz)^{2}$$

 i.e. (length of vector)² = sum of square of components

Metric

Metric tensor g_{µv} describes geometry of spacetime via the
 line element
 (ds)² = ∑g_{µv} dx_µ dx_v

Metric for flat (Euclidean) spacetime (far from any mass) (Minkowski metric)

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$(ds)^{2} = (cdt)^{2} - (dl)^{2} =$$
$$(cdt)^{2} - (dx)^{2} - (dy)^{2} - (dz)^{2}$$

μν

This means that rule for length of 4-dimensional vector is: (Length of four-vector)² = (time component)² - (length of space vector)²

Equivalence of energy and mass

$$E = \gamma mc^{2} \approx mc^{2} + \frac{1}{2}mv^{2} + \frac{3}{8}mc^{2} \cdot (\frac{v}{c})^{4} + \dots$$

energy has mass energy as one of its contributions mass is just another form of energy

- Energy can be converted into mass and vice-versa
- Consider some composite object consisting of smaller constituents;
 - as seen from the outside, object has mass M ⇒its rest energy = Mc²
 - Increasing energy of its constituents (e.g. by increasing their speeds ⇒ kinetic energies) ⇒ mass of the object increases
- Mass has energy energy has mass!
- \Box Heat piece of iron \Rightarrow increase its mass

time dilation

a clock appears to run fastest when it is at rest relative to the observer, and its rate seems to be slowed down by a factor ("Lorentz factor" γ

when the clock is moving with a velocity v relative to the observer: π

$$T = \gamma \cdot T_o$$
 $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$, where $\beta = \frac{\nu}{c}$

- T_o = "proper time" = time between two events as measured in the "rest frame" of the clock, i.e. by an observer in a frame which is at rest with respect to the clock;
- T = time between the same two events as recorded by an observer who is in motion with respect to the clock.

Experimental evidence for time dilation

lifetime of muons:

- mean lifetime of muons ="proper lifetime" (i.e. in muon's rest frame) = τ_{muon} = 2.197.10⁻⁶ sec
- experiment:

store muons in a ring ("Muon Storage Ring"), where they circulate with speed v= 0.99942 c;

- \Rightarrow the Lorentz factor γ = 29.36; mean lifetime observed in "laboratory frame" = 64.4µs, in good agreement with expected value
- Cosmic ray muons reach Earth's surface even though time as seen by Earth-based observers far exceeds their proper lifetime
- Experiment: atomic clocks travel around the Earth in jet; after return, compare with identical clock that had been left behind – deviation in agreement with expectations

Length contraction

The measured length of an object is maximum when the object is at rest relative to the observer, and appears contracted by a factor 1/γ to an observer who is in motion relative to the object:

$$L = \frac{L_o}{\gamma}$$
 $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$, (with $\beta = \frac{v}{c}$)

- L_o = "proper length" = length of object measured in its own rest frame;
- L = length measured by moving observer
- observer sees length shortened L<L_o
- □ We see length contraction of the lunar orbit
 - squished a bit in the direction of the earth's travel around the sun

Simultaneity

Def.: simultaneity:

 two events taking place at two different points in a particular reference frame are simultaneous if they can be triggered by light signals emitted simultaneously from a point halfway between them.

simultaneity has no absolute meaning, it depends on the frame of reference;

two events at two different positions which are simultaneous in one inertial frame are not simultaneous in a different inertial frame which is in motion with respect to the first one.

""" "simultaneous at same position" does have absolute meaning, i.e. is "an invariant statement".

Mass and energy

- Energy and momentum combined in 4-vector
- Lorentz transformation provides rule for expressing energy and momentum in different reference frames; energy and momentum are "mixed" just like time and position
- quantity invariant under Lorentz transformation is the length of the momentum 4-vector = the rest mass of the object (e.g. particle)
- object's rest frame = that frame in which 3-momentum = 0, the energy (time component of 4-vector) reduces to mc² = "rest energy", rest mass

$$p = (E, c\vec{p}) = (m\gamma c^2, c\vec{p}) = (m\gamma c^2, m\gamma c\vec{v})$$
$$E = \sqrt{(mc^2)^2 + (c\vec{p})^2}$$

Experimental Confirmation

- □ We see time dilation in particle lifetimes
 - in accelerators, particles live longer at high speed
 - o their clocks are running slowly as seen by us
 - o seen daily in particle accelerators worldwide

cosmic rays make muons in the upper atmosphere

- o these muons only live for about 2 microseconds
- o if not experiencing time dilation, they would decay before reaching the ground, but they *do* reach the ground in abundance
- □ We see length contraction of the lunar orbit
 - squished a bit in the direction of the earth's travel around the sun
- \Box *E* = *mc*² extensively confirmed
 - nuclear power/bombs
 - sun's energy conversion mechanism
 - bread-and-butter of particle accelerators

Summary: consequences of SR (1)

□ Consequences of special relativity (SR):

Relativity of simultaneity, time dilation, length contraction,

 Lorentz factor these



plays an important role in all of

 Time dilation: clock runs fastest when at rest wrt observer (shows "proper time" in its own rest frame), and its rate seems to be slowed down by a factor ("Lorentz factor"γ) when the clock is moving with a velocity v relative to the observer:

length contraction: length of object (in direction of motion) maximal when measured by observer at rest wrt object ("proper length" = length in its own rest frame) and appears contracted by a factor 1/γ to an observer who is in motion relative to the object

Summary: consequences of SR (2)

- □ 4-dimensional spacetime:
 - 4-dimensional spacetime: points in spacetime correspond to "events" – time and place
 - metric different from "normal" 3-dimensional space prescription for calculation of length of a vector
 - four-vectors:

o time and position $x = (ct, \vec{x}) = (ct, x, y, z) = (ct, x_1, x_2, x_3)$

o energy and momentum

$$p = (E, c\vec{p}) = (m\gamma c^{2}, c\vec{p}) = (mc^{2}\gamma, cp_{x}, cp_{y}, cp_{z})$$
$$E = m\gamma c^{2} = mc^{2} + K = \sqrt{(mc^{2})^{2} + (c\vec{p})^{2}}$$

o (Length of four-vector)² = (time component)² - (length of space vector)²

o "length" of four-vector is invariant under Lorentz transformation energy-momentum 4-vector: "length" = mc^2

Consequences of SR (3)

- Equivalence of mass and energy: mass is a form of energy, "mass has energy", "energy has mass", mass energy can be converted into kinetic energy and vice versa
 - Energy is smallest in rest frame of object
 - rest energy $E_{rest} = mc^2$ = length of energy-momentum 4-vector
 - for observer moving wrt object: $E = \gamma mc^2$
- for composite particles and other composite systems, mass includes contribution from internal energy
 - increasing internal energy of object increases its mass
 - mass of an object depends on mass of constituents and on how constituents are bound to each other to form the object
 - E.g. mass of proton, neutron > mass of quarks (contribution from motion of constituents – quarks and (massless) gluons
 - For nuclei: mass of nuclei < sum of masses of nucleons making up the nucleus – "binding energy"
 - Macroscopic objects: increase internal energy ⇒ mass increases (pot of hot coffee more massive than cold coffee)

Recap: Special theory of relativity

- Two principles:
 - o Principle of Relativity:
 - The laws of physics are the same in all inertial frames, i.e. all inertial frames are equivalent.
 - o Principle of the Constancy of the speed of light:
 The speed of light in free space (vacuum) is always
 constant = c, independent of the relative motion of
 the inertial frames, the source, and the observer.
- leads to a new concept of space and time ⇒ neither space nor time are "absolute", speed of light is
- Leads to equivalence of mass and energy mass is just another form of energy

the atomic bomb

□ "Einstein is the father of the atomic bomb"?

- not really
- 1905 Einstein: "Es ist nicht ausgeschlossen, daß bei Körpern, deren Energieinhalt in hohen Maße veränderlich ist (z. B. bei den Radiumsalzen), eine Prüfung der Theorie gelingen wird." ("It is not impossible that with bodies whose energy-content is variable to a high degree (e.g. with radium salts) the theory may be successfully put to the test.")
- 1933 Leo Szilard suggests the possibility of a nuclear chain reaction
- 1938 Otto Hahn, Fritz Straßman and Lise Meitner discover the fission of uranium nuclei
- 1939 Szilard and Enrico Fermi show that a chain reaction of fission of uranium nuclei with neutrons is possible
- 1939 Szilard convinces Einstein to sign a letter to Roosevelt about the dangers of a fission bomb.

Einstein's letter to Roosevelt, Aug. 1939

Albert Einstein Old Grove Rd. Nassau Point Peconic, Long Island

August 2nd, 1939

P.D. Roosevelt, President of the United States, White House Washington, D.C.

Sirı

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium, by which wast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air. -2-

The United States has only very poor ores of uranium in moderate ... quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work, which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

> Yours very truly. #. Senstein (Albert Einstein)

Einstein and the bomb - cont'd

- 1941 Manhattan Project launched. (Einstein carefully kept out of the project, but he is participating in a project of the Navy on explosive substances).
- 1945 Atomic bombs dropped on Hiroshima and Nagasaki. Approximately 200000 (direct) deaths. Japan surrenders unconditionally.
- □ After 1945: Einstein regrets signing the letter. Opposes the arms race and the anti-communist witch-hunt in the USA. Advocates for a world government.
- □ 1955 The Russell-Einstein manifesto: the Pugwash movement (1957).



Explosion of Fat Man over Nagasaki



The Russell-Einstein Manifesto

Written by Bertrand Russell and Albert Einstein

- Issued by Bertrand Russell in London 9 July 1955 in the middle of the Cold War
- Albert Einstein had signed it just before his death on 18 April 1955
- Shortly after release of the manifesto, Cyrus Eaton (Canadian-American banker – philanthropist) offered to sponsor a conference in his birth place Pugwash, Nova Scotia
- Led to Pugwash Conferences on Science and World Affairs <u>http://pugwash.org/</u>

In the tragic situation which confronts humanity, we feel that scientists should assemble in conference to appraise the perils that have arisen as a result of the development of weapons of mass destruction, and to discuss a resolution in the spirit of the appended draft.

We are speaking on this occasion, not as members of this or that nation, continent, or creed, but as human beings, members of the species Man, whose continued existence is in doubt. The world is full of conflicts; and, overshadowing all minor conflicts, the titanic struggle between Communism and anti-Communism.

Almost everybody who is politically conscious has strong feelings about one or more of these issues; but we want you, if you can, to set aside such feelings and consider yourselves only as members of a biological species which has had a remarkable history, and whose disappearance none of us can desire.

We shall try to say no single word which should appeal to one group rather than to another. All, equally, are in peril, and, if the peril is understood, there is hope that they may collectively avert it.

We have to learn to think in a new way. We have to learn to ask ourselves, not what steps can be taken to give military victory to whatever group we prefer, for there no longer are such steps; the question we have to ask ourselves is: what steps can be taken to prevent a military contest of which the issue must be disastrous to all parties? The general public, and even many men in positions of authority, have not realized what would be involved in a war with nuclear bombs. The general public still thinks in terms of the obliteration of cities. It is understood that the new bombs are more powerful than the old, and that, while one A-bomb could obliterate Hiroshima, one H-bomb could obliterate the largest cities, such as London, New York, and Moscow.

No doubt in an H-bomb war great cities would be obliterated. But this is one of the minor disasters that would have to be faced. If everybody in London, New York, and Moscow were exterminated, the world might, in the course of a few centuries, recover from the blow. But we now know, especially since the Bikini test, that nuclear bombs can gradually spread destruction over a very much wider area than had been supposed.

It is stated on very good authority that a bomb can now be manufactured which will be 2,500 times as powerful as that which destroyed Hiroshima.

Such a bomb, if exploded near the ground or under water, sends radio-active particles into the upper air. They sink gradually and reach the surface of the earth in the form of a deadly dust or rain. It was this dust which infected the Japanese fishermen and their catch of fish.

No one knows how widely such lethal radio-active particles might be diffused, but the best authorities are unanimous in saying that a war with H-bombs might possibly put an end to the human race. It is feared that if many H-bombs are used there will be universal death, sudden only for a minority, but for the majority a slow torture of disease and disintegration.

Many warnings have been uttered by eminent men of science and by authorities in military strategy. None of them will say that the worst results are certain. What they do say is that these results are possible, and no one can be sure that they will not be realized. We have not yet found that the views of experts on this question depend in any degree upon their politics or prejudices. They depend only, so far as our researches have revealed, upon the extent of the particular expert's knowledge. We have found that the men who know most are the most gloomy.

Here, then, is the problem which we present to you, stark and dreadful and inescapable: Shall we put an end to the human race; or shall mankind renounce war? People will not face this alternative because it is so difficult to abolish war.

The abolition of war will demand distasteful limitations of national sovereignty.² But what perhaps impedes understanding of the situation more than anything else is that the term "mankind" feels vague and abstract. People scarcely realize in imagination that the danger is to themselves and their children and their grandchildren, and not only to a dimly apprehended humanity. They can scarcely bring themselves to grasp that they, individually, and those whom they love are in imminent danger of perishing agonizingly. And so they hope that perhaps war may be allowed to continue provided modern weapons are prohibited.

This hope is illusory. Whatever agreements not to use H-bombs had been reached in time of peace, they would no longer be considered binding in time of war, and both sides would set to work to manufacture H-bombs as soon as war broke out, for, if one side manufactured the bombs and the other did not, the side that manufactured them would inevitably be victorious.

Although an agreement to renounce nuclear weapons as part of a general reduction of armaments would not afford an ultimate solution, it would serve certain important purposes.

First, any agreement between East and West is to the good in so far as it tends to diminish tension. Second, the abolition of thermo-nuclear weapons, if each side believed that the other had carried it out sincerely, would lessen the fear of a sudden attack in the style of Pearl Harbor, which at present keeps both sides in a state of nervous apprehension. We should, therefore, welcome such an agreement though only as a first step.

Most of us are not neutral in feeling, but, as human beings, we have to remember that, if the issues between East and West are to be decided in any manner that can give any possible satisfaction to anybody, whether Communist or anti-Communist, whether Asian or European or American, whether White or Black, then these issues must not be decided by war. We should wish this to be understood, both in the East and in the West.

There lies before us, if we choose, continual progress in happiness, knowledge, and wisdom. Shall we, instead, choose death, because we cannot forget our quarrels? We appeal as human beings to human beings: Remember your humanity, and forget the rest. If you can do so, the way lies open to a new Paradise; if you cannot, there lies before you the risk of universal death. Resolution:

We invite this Congress, and through it the scientists of the world and the general public, to subscribe to the following resolution:

"In view of the fact that in any future world war nuclear weapons will certainly be employed, and that such weapons threaten the continued existence of mankind, we urge the governments of the world to realize, and to acknowledge publicly, that their purpose cannot be furthered by a world war, and we urge them, consequently, to find peaceful means for the settlement of all matters of dispute between them."

Signatories:

Max Born Percy W. Bridgman Albert Einstein Leopold Infeld Frédéric Joliot-Curie Herman J. Muller Linus Pauling Cecil F. Powell Joseph Rotblat Bertrand Russell Hideki Yukawa

http://pugwash.org/1955/07/09/statement-manifesto/

AE milestones 1906-1910

1906

- Promoted to "technical expert 2nd class"
- **1**907
 - Quantum theory of the specific heat
 - "Glücklichster Gedanke" (falling body does not feel gravity) ⇒ Start of work on general relativity.
 - Predicts redshift and deflection of light in a gravitational field and planetary orbits differing from Newton: Mercury perihelion motion

1908

- Habilitation at the University of Bern -- Privatdozent (unpaid)
- Working on "Maschinchen" (electrostatic potential multiplier) with the brothers Habicht.

1909

- Statistical wave-particle complementarity of radiation.
- Assistant professor at the University of Zurich; Kleiner: "Today, Einstein is one of the most important theoretical physicists ..."
- Resigns at the patent office
- Honorary Doctorate of Geneva University



http://www.einstein-website.de/z_biography/maschinchen-e.html

AE Milestones 1910 - 1912

1910

- Theory of critical opalescence.
- Birth of his second son Eduard ("Tede" later "Teddy").
- develops a dislike for lecture and contempt for the established order.

1911

- Professor at the German University of Prague (for 18 months)
- Meets Paul Ehrenfest
- First version of general relativity
- **1**912
 - Professor at the ETH Zürich (invitation due to Felix Kleiner, Marcel Grossmann...)
 - Realizes errors in his first version of GRT.
 - Begins a study of curved spaces in collaboration with Grossmann ("Grossmann, Du mußt mir helfen, sonst werd' ich verrückt!").
 - Second version of general relativity.





AE Milestones 1912 - 1912

1913

- "Entwurf einer verallgemeinerten Relativitätstheorie und einer Theorie der Gravitatation" (Outline of a general theory of relativity and a theory of gravitation) with Marcel Grossmann (Z. f. Phys.)
- Elected member of the Prussian Academy of Sciences
- Appointed Director of the "Forschungsinstitut f
 ür Physik der Kaiser-Wilhelm-Gesellschaft" (opens in 1917)
- Professor at University Berlin (no teaching obligation)
- **1**914
 - Family moves to Berlin
 - Coming out" as pacifist and internationalist.
 - Signs with several others the "Aufruf an die Europäer" ("Manifesto to the Europeans." (<u>http://eutopiamagazine.eu/de/albert-einstein/columns/aufruf-die-europäer</u>)
 - Joins the pacifist "Bund Neues Vaterland".
 - Mileva returns with the children to Zürich.

Albert Einstein, Georg Nicolai: Aufruf an die Europäer (30 Dec 1914)

....Denn der heute tobende Kampf wird kaum einen Sieger, sondern wahrscheinlich nur Besiegte zurücklassen. Darum scheint es nicht nur gut, sondern bitter nötig, daß gebildete Männer aller Staaten ihren Einfluß dahin aufbieten, daß - wie auch der heute noch ungewisse Ausgang des Krieges sein mag – die Bedingungen des Friedens nicht die Quelle künftiger Kriege werden, daß vielmehr die Tatsache, daß durch diesen Krieg alle europäischen Verhältnisse in einen gleichsam labilen und plastischen Zustand geraten sind, dazu benutzt werde, um aus Europa eine organische Einheit zu schaffen. Die technischen und intellektuellen Bedingungen dafür sind gegeben.

In welcher Weise diese Ordnung Europas möglich ist, soll hier nicht erörtert werden. Wir wollen nur grundsätzlich betonen, daß wir fest davon überzeugt sind, daß die Zeit da ist, in der Europa als Einheit auftreten muß, um seinen Boden, seine Bewohner und seine Kultur zu schützen.... ...The struggle raging today will hardly produce any victor; but rather will probably leave only defeated ones. Therefore, it seems not only good, but rather bitterly *necessary that educated men of all nations* marshal their influence such that whatever the still uncertain end of the war may be — the terms of peace shall not become the wellspring of future wars, but rather that the evident fact that through this war all European relational conditions have slipped into an unstable and malleable state, should be used to form Europe into an organic integrated whole. The technological and intellectual conditions for this are extant.

In which manner this (new) ordering in Europe is possible, shall not be deliberated here. We want merely to emphasize very fundamentally that we are firmly convinced that the time has come where Europe must act as one in order to protect her soil, her inhabitants, and her culture.....

http://eutopiamagazine.eu/en/albert-einstein/columns/manifesto-europeans

AE Milestones

1915

- New version of the GRT gives 43 arc-sec for the perihelion motion of Mercury, in agreement with observation. "For a few days I was beside myself with joy."
- Die Feldgleichungen der Gravitation" submitted to the Prussian Academy of Sciences (on 25 November) after "langen Irrwegen" (long erroneous paths) with "übermenschliche Anstrengungen" (superhuman exertion) and " zufrieden, aber ziemlich kaputt" (content, but rather exhausted)
- Prediction of light deflection by the sun: 1.7 arc second.

1916

- Publication of GRT: "Die Grundlage der allgemeinen Relativitätstheorie" (Ann. d. Phys. 49, pp 769-822 (1916)
- Predicts gravitational waves.

844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation. Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen¹ habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die NEWTONSCHE Theorie als Näherung enthalten und heliebigen Substitutionen von der Determinante 1 gegenüber kovariant waren. Hierauf fand ich, daß diesen Gleichungen allgemein kovariante entsprechen, falls der Skalar des Energietensors der «Materie« verschwindet. Das Koordinatensystem war dann nach der einfachen Regel zu spezialisieren, daß $\sqrt{-g}$ zu i gemacht wird, wodurch die Gleichungen der Theorie eine eminente Vereinfachung erfahren. Dabei mußte aber, wie erwähnt, die Hypothese eingeführt werden, daß der Skalar des Energietensors der Materie verschwinde.

Neuerdings finde ich nun, daß man ohne Hypothese über den Energietensor der Materie auskommen kann, wenn man den Energietensor der Materie in etwas anderer Weise in die Feldgleichungen einsetzt, als dies in meinen beiden früheren Mitteilungen geschehen ist. Die Feldgleichungen für das Vakuum, auf welche ich die Erklärung der Perihelbewegung des Merkur gegründet habe, bleiben von dieser Modifikation unberührt. Ich gebe hier nochmals die ganze Betrachtung, damit der Leser nicht genötigt ist, die früheren Mitteilungen unausgesetzt heranzuziehen.

Aus der bekannten RIEMANNSCHEN Kovariante vierten Ranges leitet man folgende Kovariante zweiten Ranges ab:



(1b)

⁴ Sitzungsber, XLIV, S. 778 und XLVI, S. 799, 1913
AE Milestones 1916 - 1917

1916

- president of the Deutsche Physikalische Gesellschaft (succeeding Max Planck)
- Arthur Eddington sees E's general relativity paper (via Willem de Sitter)
 is convinced, starts planning an expedition

1917

- becomes very sick (liver problems, and ulcer symptoms and jaundice), bed-ridden for several months; Elsa Einstein Löwenthal takes care of him
- First paper on cosmology based on GRT ("Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie"); has "cosmological constant" added to allow static solution (1930: "The biggest blunder of my life"); paper forms basis for all of modern cosmology
- "Zur Quantentheorie der Strahlung" (Quantum Theory of Radiation) shows possibility of stimulated emission of radiation (⇒ laser); new derivation of Planck's radiation law
- Oct: Kaiser Wilhelm Institute starts operation, AE director

AE Milestones 1919

1919

- divorce from Mileva, marries Elsa
- Expedition of Royal Society of London (Arthur Eddington) to observe solar eclipse (29 May) and verify light deflection

• Telegram from Lorentz to AE:

"Eddington fand Sternverschiebung am Sonnenrand vorläufig zwischen neun zehntel Sekunde und doppeltes".

Publication: Test of the General Theory of Relativity (Naturwiss. 7 (1919),776):"Nach einem von Prof. Lorentz an den Unterzeichneten gerichteten Telegramm hat die zur Beobachtung der Sonnenfinsternis am 29. Mai ausgesandte englische Expedition unter Eddington die von der allgemeinen Relativitätstheorie geforderte Ablenkung des Lichtes am Rande der Sonnenscheibe beobachtet. Der bisher provisorisch ermittelte Wert liegt zwischen 0.9 und 1.8 Bogensekunden. Die Theorie fordert 1.7." (preliminary result of measurement of deflection: value between 0.9 and 1.8 arc sec, predicted value is 1.7)







Test of General Relativity 1919

□ 6 November 1919:

- joint meeting of the Royal Society and the Royal Astronomical Society:
- measured light deflection 1.98" ± 0.30" in Sobral and 1.61" ± 0.30" in São Thomé e Príncipe
- chairman J.J. Thomson:
 - "The deflection of light by matter, suggested by Newton in the first of his Queries, would itself be a result of first-rate scientific importance; it is of still greater importance when its magnitude supports the law of gravity put forward by Einstein"



http://www.mpg.de/9244824/solar-eclipse-1919 http://astrogeo.oxfordjournals.org/content/50/4/4.12.full http://www.esa.int/Our_Activities/Space_Science/Relativity_and_the_1919_eclipse http://w.astro.berkeley.edu/~kalas/labs/documents/kennefick_phystoday_09.pdf http://news.bbc.co.uk/2/hi/science/nature/8061449.stm

7 November **1919** London Times p 12 col 6:

LIGHTS ALL ASKEW

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

New York Times of 10 November 1919

REVOLUTION IN SCIENCE.

NEW THEORY OF THE UNIVERSE.

NEWTONIAN IDEAS OVERTHROWN.

Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results obtained by British observers of the total solar eclipse of May 29 were discussed.

The greatest possible interest had been aroused in scientific circles by the hope that rival theories of a fundamental physical problem would be put to the test, and there was a very large attendance of astronomers and physicists. It was generally accepted that the observations were decisive in the verifying of the prediction of the famous physicist, Einstein, stated by the President of the Royal Society as being the most remarkable scientific event since the discovery of the predicted existence of the planet Neptune. But there was difference of opinion as to whether science had to face merely a new and unexplained fact, or to reckon with a theory that would completely revolutionize the accepted fundamentals of physics.

SIR FRANK DYSON, the Astronomer Royal, described the work of the expeditions sent respectively to Sobral in North Brazil and the island of Principe, off the West Coast of Africa. At each of these places, if the weather were propitious on the day of the eclipse, it would be possible to take during totality a set of photographs of the obscured sun and of a number of bright stars which happened to be in its immediate vicinity. The desired object was to ascertain whether the light from these stars, as it passed the sun, came as directly towards us as if the sun were not there, or if there was a deflection due to its presence, and if the latter proved to be the case, what the amount of the deflection was. If deflection did occur, the stars would appear on the photographic plates at a measurable distance from their theoretical positions. Ho explained in detail the apparatus that had been employed, the corrections that had to be made for various disturbing factors, and the methods by which comparison between the theoretical and the observed positions had been made. He convinced the meeting that the results were definite and conclusive, Deflection did take place, and the measurements showed that the extent of the deflection was in close accord with the theoretical degree predicted by Einstein, as opposed to half that degree, the amount that would follow from the principles of Newton. It is interesting to recall that Sir Oliver Lodge, weaking at the Royal Institution last February, had also ventured on a prediction. He doubted it deflection would be observed, but was confident that if it did take place, it would follow the law of Newton and not that of Einstein.

DR. CROMMELIN and PROFESSOR EDDINGTON, two of the actual observers, followed the Astronomer-Royal, and gave interesting accounts of their work, in every way confirming the general conclusions that

" MOMENTOUS PRONOUNCEMENT."

So far the matter was clear, but when the discussion began, it was plain that the scientific interest centred more in the theoretical bearings of the results than in the results themselves. Even the President of the Royal Society, in stating that they had just listened to "one of the most momentous, if not the most momentous, pronouncements of human thought," had to confess that no one had yet succeeded in stating in clear language what the theory of Einstein really was. It was accepted, however, that Einstein, on the basis of his theory, had made three predictions. The first, as to the motion of the planet Mercury, had been verified. The second, as to the existence and the degree of deflection of light as it passed the sphere of influence of the sun, had now been verified. As to the third, which depended on spectroscopic observations there was still uncertainty. But he was confident that the Einstein theory must now be reckoned with, and that our conceptions of the fabric of the universe must be fundamentally altered.

At this stage Sir Oliver Lodge, whose contribution to the discussion had been eagerly expected, left the meeting.

Subsequent speakers joined in congratulating the observers, and agreed in accepting their results. More than one, however, including Professor Newall, of Cambridge, hesitated as to the full extent of the inferences that had been drawn and suggested that the phenomena might be due to an unknown solar atmosphere further in its extent than had been supposed and with unknown properties. No speaker succeeded in giving a clear non-mathematical statement of the theoretical question.

SPACE "WARPED."

Put in the most general way it may be described as follows : the Newtonian principles assume that space is invariable, that, for instance, the three angles of a triangle always equal, and must equal, two right angles. But these principles really rest on the observation that the angles of a triangle do equal two right angles, and that a circle is really circular. But there are certain physical facts that seem throw doubt on the universality to of these observations, and suggest that space may acquire a twist or warp in certain circumstances, as, for instance, under the influence of gravitation, a dislocation in itself slight and applying to the instruments of measurement as well as to the things measured. The Einstein doctrine is that the qualities of space, hitherto believed absolute, are relative to their circumstances. He drew the inference from his theory that in certain cases actual measurement of light would show the effects of the warping in a degree that could be predicted and calculated. His predictions in two of three cases have now been verified, but the question remains open as to whether the verifications prove the theory from which the predictions wore deduced.

□ 7 November article in the London Times:

- "Revolution in science New theory of the universe - Newtonian ideas overthrown- Space warped"
- 9 November press release in The New York Times:
 - "Einstein theory triumphs Stars not where they seem or were calculated to be, but nobody need worry"
- 19 November Lorentz in the Nieuwe Rotterdamse Courant
- 23 November Born in the Frankfurter Allgemeine Zeitung
- 28 November Einstein in the London Times:
 - "It was in accordance with the high and proud tradition of English science that English scientific men should have given their time and labor [...] to test a theory that had been completed and published in the country of their enemies in the midst of war. [...]

14 December 1919 Berliner Illustrirte Zeitung:

> • Eine neue Größe der Weltgeschichte: Albert Einstein



Eine neue Größpe ber Bettgeschichte: Albert Einftein, m boffen Joefdungen eine willige Unwählung nuferer Reintwickatung vobutes und ban etrenntiffen eines Repertund Reiben gleichnereitig find.

Path to GRT

□ Principle of special relativity:

- All inertial frames are equivalent ⇒ observed phenomena are independent of the state of motion of the observer, as long as observer a rest in an inertial frame.
- Can we extend this to non-inertial systems? For example, to a braking train or a carousel?
- Can one formulate a "principle of general relativity"?
- Commonality of gravitation and electromagnetism:
 - both understood as field: mass changes the space just like charge does
 - change propagates with the speed of light.
 - No "immediate effect at a distance."

Einstein's quest to General Relativity

1907:

- AE preparing a review paper on Special Relativity
- Begins wondering about how to modify gravity to make it compatible with special relativity
- "glücklichster Gedanke meines Lebens" ("the luckiest thought of my life"): "The gravitational field leads to only a relative existence, in the same way as an electric field which is caused by magnetic induction. Because for an observer falling freely from the roof of a house there is [...] no gravitational field."
- equivalence principle that "... 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."

□ 1907 Following this, toiling for 9 years...

Extension to non-inertial frames

Extension is not obvious:

- you feel that the train slows down,
- you feel that the carousel rotates, so you're in motion, not in a rest frame.
- The lucky thought: the phenomena in a braking train can not be distinguished from those in a train at rest if you have a suitable gravitational field acting on the train at rest, because ... the gravitational acceleration is the same for each object in the train, just as the braking acceleration





- Woman in elevator throws ball horizontally towards the wall with speed u
- Observer in elevator:
 - If elevator moves with constant velocity: sees ball fly horizontally (solid line)
 - If elevator accelerated up, ball moves with • constant velocity wrt elevator when it was launched
 - But elevator accelerates \Rightarrow ball appears to fall
- Observer outside (in inertial frame):
 - in both cases sees ball move in straight line, 0 with vertical component = v, horizontal component = u



□ solid line: seen by observer inside the elevator

□ dashed line: seen by observer outside (in inertial frame)

Another elevator..

 Elevator in gravityfree environment, accelerating upwards
 Throwing a ball horizontally in upward accelerating elevator

- Left: Seen by outside inertial observer
- Right: seen by observer inside the elevator



Motion in accelerated frame and in gravitational field

observer in elevator cabin

- sound-proof elevator cabin with no windows,
- no means to communicate with the outside world
- cabin is being accelerated or placed on the Earth surface.
- The observer throws stones and watches their motion. What does the observer see?



- To the elevator observer, results of the measurements are the same in the gravitation field and in an accelerated frame.
- observer cannot tell between the two --- acceleration and gravitation produce the same effect.

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Free-falling observer: no gravity!

now compare observations of an observer in the absence of gravity, in free-fall near Earth, and standing still on surface of Earth.



- Observer in the absence of gravity measures the same results as does the free-falling observer
- Why? Because as the free-falling observer is moving in the Earth's gravitation field, so does the object.
- For the observer in free fall, object moves along a straight line! Freefall frame is truly inertial (as long as it is small enough – local); gravity does not exist for a freefalling observer.

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Gravitation = Geometrical Distortions



Film clip from Nova/PBS http://www.pbs.org/wgbh/nova/einstein/rela-i.html

principle of equivalence:

• principle of equivalence:

being in a gravitational field is equivalent to being in an accelerated frame of reference; there is no experiment or measurement performed entirely inside our laboratory (our frame of reference) that allows us to determine if we are accelerating in the absence of gravity or are at rest in a gravitational field.

 This assumption extends the principle of relativity to the case of uniformly accelerated motion of the reference frame.

Curved space

- □ Equivalence principle, equivalence of all accelerating frames ⇒ space cannot be Euclidean
- Einstein "did not know enough mathematics" needed to study Riemannian geometry
- □ Recall: the equivalence of all *inertial* (i.e. non-accelerating) frames ⇒ Special Relativity. The postulate of equivalence of all *accelerating* or *non-inertial* frames ⇒General Relativity.
- $\Box \Rightarrow$ Space not Euclidean \Rightarrow curved spacetime!
- gravitation is not a physical force, but rather a consequence of curved spacetime;
- □ curvature of spacetime ⇒ masses want to move towards each other

Astronomical observations

- equivalence principle:
 - effects of gravitation and acceleration are the same ⇒ bending of light in the vicinity of massive bodies
- □ Curved spacetime:
 - geodesics (shortest paths between points) not straight lines, light follows geodesics ⇒ bending
- **1**911:
 - AE proposes an astronomical method to measure the deflection of light: measuring positions of stars as Sun passes in front of them – during a solar eclipse, so that stars can be seen
 - But value of deflection calculated by him in 1911 off by factor of 2

The Einsteinturm – "Einstein Tower" built in Potsdam around 1920 to measure the deflection of star light by the Sun



1913 Letter from Einstein to George Ellery Hale (director of Mt. Wilson observatory) suggesting to measure the deflection of light passing close to the Sun.

Hale responds: is only measurable at a solar eclipse;

Several expeditions planned, but... first World War breaks out.

> 0.84 arc second (too small by factor 2)

Zariel. 14. X. 13. Roch quelister Hers Kollege! time surfache theoretische Ufor legung macht die Annahmes plansitel, dass Lichtstrahlen in einem Geavitations. felde eme Deviation uphren. 5 Lechtetahl An Somewande misste diese Ablenberry 0,84 betrayer und wie - abuchmen - unalpunket) To mare deshall von geösstem whe ground Firsteene bei Annendung der stinketen Vergrösserungere ber Tage (ohne Somerfinsternis) gereken werden komun

Straight line – always the shortest distance?

- Term "geodesics" is a generalization of the notion of "straight line", when applied to a curved space.
- \Box shortest distance between two points = straight line always???
- □ Sometimes it is, sometime it isn't!



Shortest distance on a plane is a straight line



Shortest distance on a sphere is an arc of a great circle

Path of airplanes

□ path of airliners:

- the shortest path between airports = geodesic on the surface of the Earth
- which at first sight doesn't seem like the shortest!
- name "geodesics": from geodesy the science of measuring the size and shape of Earth.



How to find the geodesics?

□ definition of a geodesic line

- \bullet = locally shortest path between two points on a metric.
- geodesics thus describe the motion of free particles.
- geodesics are the world lines of a free particles in a given metric
- □ world line of a free particle in Special Relativity:
 - Straight line
 ⇒ geodesics of Minkowski metric = straight lines

\Box in general:

 geodesic between two points can be found by writing down the equation for the length of a curve, then minimizing the length of the curve using standard techniques of calculus and differential equations

□ for length of curve, need to know metrics of space – "metric tensor"

$$ds^{2} = \sum_{\mu=0}^{3} \sum_{\nu=0}^{3} g_{\mu\nu} dx^{\mu} dx^{\nu} = g_{00} dx^{0} dx^{0} + g_{01} dx^{0} dx^{1} + \dots + g_{33} dx^{3} dx^{3} dx^{3}$$

GENERAL THEORY OF RELATIVITY

Special theory of relativity: Laws of physics are same for all observers in inertial reference frames (i.e. unaccelerated observers);

What about accelerated observers?

Albert Einstein (1915):
 "Die Grundlage der allgemeinen Relativitätstheorie" (The foundation of the general theory of relativity)

Principle of general relativity:

The laws of nature are to be expressed by equations which hold in all frames of reference (systems of coordinates), i.e. are "covariant" with respect to any substitutions (i.e. there are appropriate coordinate transformations to relate description in one frame of reference to another); every accelerated observer experiences the same laws of nature;

"Die Grundlage der allgemeinen Relativitätstheorie"



1. Die Grundlage der allgemeinen Belattvitätstheorie; von A. Einstein.

AS 7.

Die im nachfolgenden dargelegte Theorie bildet die denkbie im macmoigenden uargenegre zneorie onder die denk-tar weitgehendste Verallgemeinerung der heute allgemein als her wengenemeste verangememerung der neue angemennen. Relativitätstheorie" bezeichneten Theorie; die letztere nenne h im folgenden zur Unterscheidung von der ersteren "spezielle lativitätstheorie" und setze sie als bekannt voraus. Die allgemeinerung der Relativitätstheorie wurde sehr erfert durch die Gestalt, welche der speziellen Relativitätsie durch Minkowski gegeben wurde, welcher Matheer zuerst die formale Gleichwertigkeit der räumlichen naten und der Zeitkoordinate klar erkannte und für dbau der Theorie nutzbar machte. Die für die all-Relativitätstheorie nötigen mathematischen Hilfsten fertig bereit in dem "absoluten Differentialkalkül", auf den Forschungen von Gauss, Riemann und tidel über nichteuklidische Mannigfaltigkeiten ruht und Ricci und Levi-Civita in ein System gebracht und Probleme der theoretischen Physik angewendet habe im Abschnitt B der vorliegenden Abhandfor uns nötigen, bei dem Physiker nicht als bekannt iden mathematischen Hilfsmittel in möglichst and durchsichtiger Weise entwickelt, so daß ein matischer Literatur für das Verständnis der a Abhandlung nicht erforderlich ist. Endlich sei telle dankbar meines Freundes, des Mathematikers lacht, der mir durch seine Hilfe nicht nur einschlägigen mathematischen Literatur erern mich auch beim Suchen nach den Feldgleicht

The Field Equation

To take into account spacetime curvature, tensor calculus was necessary in Einstein's General Relativity.



Geometry of space

The geometry of space is determined by the distribution of gravitational matter

□ Consequences of these principles:

- "space is warped"("non-Euclidean")
 "geodesic lines" (= shortest connections between two points) are not necessarily straight lines;
- light passing near a massive object is bent; (i.e. light has gravitational mass!)
- gravitational mass = inertial mass
- gravitational radiation
- gravitational redshift
- clocks go slower near mass
- yardsticks shorter near mass
- perihelion precession of Mercury
- black holes
- expansion (or contraction) of the Universe

Field Equations of GR

- □ GR field equations = set of 10 coupled non-linear partial differential equations for the components of the metric tensor
- "solution" of the field equation = the metric tensor (all of its components)
- solution mathematically very difficult, solutions have been found only for some special cases
 - E.g. Schwarzschild, de Sitter, Friedmann, Robertson, Walker,..
- □ Einstein's Field Equation: (just for fun...)

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} Rg_{\mu\nu} = \frac{8\pi}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

 $-\Lambda$ = Cosmological Constant (added 1917) Einstein's "Biggest Blunder" (resurrected as dark energy)

 $G_{\mu\nu}$ = Einstein Tensor describing how spacetime is curved; $R_{\mu\nu}$ = Ricci curvature tensor, $g_{\mu\nu}$ = metric tensor, R = Ricci curvature number

Stress-Energy Tensor describing distribution of mass and energy

Special case: vacuum

 \Box Simplest assumption for energy-stress tensor $T_{\mu\nu}$: $T_{\mu\nu} = 0$

- □ This special case is called "vacuum", and corresponding solutions for the metric $g_{\mu\nu}$ are called "vacuum solutions". In this case, we have R = 0.
- **□** Field equation has form $R_{\mu\nu} = 0$

Note that R_{μν} are a complicated mess of derivatives of the metric.

There are many solutions for this "vacuum" equation, including several exact analytic solution.

These different solutions arise from different symmetries we impose on the metric

Minkowski metric

 Minkowski metric is one of the vacuum solutions for a space that has perfect symmetry – a space that is:

- uniform, so that $g(t,x,y,z) = g(t,x+\Delta x,y,z)$ (also true for y and z)
- isotropic, so that g(t,x,y,z) = g(t,-x,y,z) (also true for y and z)

and a time that is:

- uniform, so that $g(t,x,y,z) = g(t+\Delta t,x,y,z)$



Schwarzschild Vacuum Solution

 Another important metric, first to be explicitly solved only weeks after Einstein published his General Relativity paper is 1915, is called *Schwarzschild metric*, named after the man who solved it.

• This solution assumes *spherical symmetry* of space, as *around* an isolated star.

• How is this "vacuum" if there is a star?! There's mass, thus there is energy, and there must be stress somehow, so tensor T_{uv} must be nonzero!

• The keyword is "around" – the solution is for the metric of *empty space* (also known as "vacuum") surrounding a spherically-symmetric massive object.



Karl Schwarzschild (1873-1916)

Spacetime around a Spherical Star

Karl Schwarzschild (1916): first exact solution of Einstein's equations:

 \mathcal{O}

$$ds^{2} = c^{2} \left(1 - \frac{r_{s}}{r}\right) dt^{2} - \frac{dr^{2}}{\left(1 - \frac{r_{s}}{r}\right)} - r^{2} d\theta^{2} - r^{2} \sin^{2} d\phi^{2}$$

 $r_s = \frac{2GM}{c^2}$

r_s = "Schwarzschild radius"



Karl Schwarzschild 1873 - 1916

GR: a Genuine Scientific Revolution

□ The General Relativity view

- Relegated "gravity" to the interaction between mass and spacetime
- Abolished the notion that the geometry of spacetime is everywhere flat
- Mixed the concepts of space and time
- GR does <u>not</u> mean "everything is relative"!
 - The basic concept is that the equations/laws that describe physical systems should not depend on your reference frame.
 - Coordinate Invariance" would be a better term...
 - Einstein wanted to call it "The Theory of Invariants"

□ GR = theory of gravitation \Rightarrow applicable to the universe (cosmology).

Recap:

- Gravitation of General Relativity is not a force; it is the property of spacetime, its curvature.
- Mass curves spacetime, while curved spacetime determines the motion of mass.
- Mathematical form of General Relativity is the Einstein's Field Equation that binds together the metric (curvature) of spacetime and the stress-energy (mass distribution).
- General solution of Einstein's Field Equation is difficult; some important special-case solutions are known.

Cosmology

□ In 1919:

- The known universe only contains the galaxy.
- Many open questions:
 - o Are there stars / star systems beyond our galaxy?
 - o Is the universe static?
 - o How big is the universe?
 - o Does the universe have a beginning?
 - o What is the material and energy content of the universe?
- □ 1920 "The great debate":
 - Shapley: The galaxy is vast and includes globular systems and cloud systems of stars. The sun is located at the edge.
 - Curtis: The galaxy is small and the sun is close to the center. Outside there are other galaxies
- □ 1920-1924 Hubble:
 - Andromeda "Nebula" is outside the galaxy, and is itself a kind of galaxy.
- □ 1929 Hubble: the universe expands.

Sequel to GRT

1916:

 Schwarzschild presents the first solution of the field equations. (describes the spherically symmetric gravitational field outside a spherical, uniform and non-rotating mass distribution M)





- o (1) *r*=0 (the origin). Here space and time cease to exist.
- o (2) $r_s = 2GM/c^2$ (the Schwarzschild radius)
- Meaning of r_s : if all mass M is compressed within r_s then the light can not escape \Rightarrow black hole.
- Example: the r_s of the Earth is ...9mm
- Black holes exist -- some very massive (many solar masses);
- the center of the galaxy contains a massive black hole.



Artist's impression of a Black Hole

Big Bang

Einstein 1917

- Thinks that there are no mass-free solutions (Mach's principle).
- With the strengthening action of the masses, the universe collapses; introduces an additional term: the cosmological constant Λ, so as to make the universe static.
- De Sitter shows immediately that there exist mass free solutions. ("That man does not understand his own theory.")
- □ Friedman 1922

shows that the original field equations allow expanding solutions.

- Weyl and Eddington 1923
 - show that in the de Sitter universe test particles are moving away from each other. Einstein gives the cosmological constant up ("My biggest blunder").

Hubble 1929

 shows that the universe expands: beginning of the big bang theory.



Physics in 1919

□ Two forces:

- electromagnetism and gravitation
- described with separate field theories: Maxwell's equations for electromagnetism Einstein's field equations of GR for gravitation

□ two elementary particles:

- electron and proton form atoms
- Atoms consist of a small heavy nucleus (proton-electron combinations), surrounded at a large distance by electrons (Rutherford)

quantum postulate:

- atomic electrons can only exist in certain stationary orbits, thus only at certain energies.
- Electromagnetic radiation ("light") is created / destroyed in the transition of electrons from one to another stationary orbit (Bohr-Sommerfeld).
- radiation has both a particle and a wave character (Planck, Einstein).
Einstein after 1919

Einstein 1919

 After completion of GRT, committed to a new task: to unite the two separate field theories in a unified field theory.



- assumes that unified theory has the same structure.
 differential equations that are invariant under a (local) Lorentz transformation ("covariant").
- He hopes to get the elementary particles and the photon as result of the theory.
- finds no overarching physical principle (as, e.g. constancy of the speed of light, equivalence of inertial and gravitational mass, ..). and regularly changes his point of view: five dimensional theories versus connections.
- Ioses himself more and more in mathematics and is standing increasingly alone.

Einstein 1919 to 1955

□ He disputes or ignores further developments:

- The new quantum mechanics.
- The discovery of new particles (neutrino, neutron, meson, ...)
- The discovery of new forces (weak and strong interactions)

1905-1920

- Einstein is (almost) alone in his view of the light quantum
- Einstein the revolutionary.
- Physical principles are paramount

1920-1955

- Einstein is (almost) alone in his pursuit of unification and in his rejection of quantum mechanics
- Einstein the reactionary
- Mathematical principles come first

Albert Einstein 1919-1920

1919

- Meetings with Zionist Blumenfeld.
- Nascent Zionism. "One can have an international outlook without losing one's involvement with the members of the tribe."

□ 1920

- Extraordinary professor in Leiden.
- Patent for a gyrocompass.
- Enters into debate with Lenard about relativity
- Brings his sick mother to his home in Berlin, who dies there.
- 1920-? Has several affairs with other women. "I must seek in the stars what was not given to me on earth."
- 1920-1924 Travels through Europe and to Japan, South America and the USA Enormous public interest. Tempestuous welcome. Raises funds for the foundation of the Hebrew University in Jerusalem. Patent for a new type of refrigerator with Szilard

Albert Einstein 1921

1921 upon arrival in the US with Elsa and the Zionist leaders Chaim Weizmann and wife, Ussishkin and Mossinson





- Trip to U.S. fund-raising tour for Hebrew university of Jerusalem
 - o Lectures at Columbia University, Nat'l Academy of Sciences in Washington, Princeton
 - o Honorary Dr degree from Princeton
- On return, visit in England, lectures in London (King's College) and Manchester
- Back in Berlin, meets Leo Szilard (later collaborator)

AE Milestones 1922-1924

1922

attends physical society meeting in Vienna

- Eyewitness in Vienna: "The audience was in a peculiar state of excitement where it matters no more what one understands, only that one is in the immediate vicinity of a place where miracles happen."
- Member of the Committee for Intellectual Cooperation of the League of Nations.
- 1922 Nobel Prize for his explanation of the photoelectric effect.
- **1922-1955**
 - Publications on "Einheitliche Feldtheorie". Attempts to unify electromagnetism and gravity in a differential geometric theory -failed.
- 1922-23 journey to Palestine
 - Laid cornerstone for Hebrew University of Jerusalem
- **1**924
 - Bose-Einstein condensation and quantum gas (his last major discovery)

AE Milestones 1927-1935

- □ 1927 at fifth Solvay conference
 - Begins his dispute with Bohr about the interpretation of quantum mechanics
- 1928
 - Overtired and heart disease. Some time bedridden.
 - Helen Dukas becomes his secretary for life.
- 1932 Professor at the Institute for Advanced Study at Princeton
- **1**933
 - Hitler's "Machtergreifung"
 - Leaving Germany and settles in Princeton. Will not return to Europe
- 1935
 - Einstein Podolsky Rosen article about incompleteness of quantum mechanics from the standpoint of physical reality ("spooky action at a distance")

AE Milestones 1936-1939

□ 1936

- Elsa dies after a short illness. "I [...] live like a bear in its den and feel more at home than ever [...]. This bear-like quality has increased because of the death of my companion, who was more attached to humans [than me]. "
- On the death of Besso in 1955: "What I most admired in him was that he could live in harmony with a woman [Anna Winteler], an undertaking in which I twice failed rather miserably."

1939

- upon request from Szilard wrote a letter to President Roosevelt with a warning about the possibility of an atomic bomb.
- His sister Maja coming to Princeton. Her husband Paul Winteler remains in Paris.

AE Milestones 1940-1950

1940:

- Albert and Maja Einstein and Helen Dukas sworn in as American citizen.
- He retains his Swiss nationality.
- 1940-1945 Consultant in the Navy for heavy explosives.

1945 - 1955

plea for world government.



- Outright rejection of McCarthyism, among others because of the case of Oppenheimer.
- Einstein-Russell manifesto.
- Supporter of Israel.
- □ 1946 Maja had a stroke and is bedridden (died in 1951).
- 1949 Mileva dies
- 1950 laparoscopy because of periodic abdominal pain, probably caused by a tumor. He has an aneurysm (bulge through a weakened blood vessel wall) of the abdominal aorta. No further intervention

AE Socialist?

□ Why Socialism?, published in 1949 in the Monthly Review:

- Einstein described a chaotic capitalist society, a source of evil to be overcome, as the "predatory phase of human development". He came to the following conclusion:
- I am convinced there is only one way to eliminate these grave evils [capitalism], namely through the establishment of a socialist economy, accompanied by an educational system which would be orientedtoward social goals. In such an economy, the means of production are owned by society itself and are utilized in a planned fashion. A planned economy, which adjusts production to the needs of the community, would distribute the work to be done among all those able to work and would guarantee a livelihood to every man, woman, and child. The education of the individual, in addition to promoting his own innate abilities, would attempt to develop in him a sense of responsibility for his fellow men in place of the glorification of power and success in our present society.
- On the floor of the US Congress, Einstein accused by John E. Rankin of Mississippi of being a "foreign-born agitator" who sought "to further the spread of Communism throughout the world."

AE Milestones 1952-1955

1952

- Declines the offer to become president of Israel.
- Ben Gurion: "What would we have done if he had said yes?"

1955

 April 13, he collapsed, hospitalized. Refuses surger "I've done my bit, it's time to go." Working in the hospital on a speech on the occasion of Israel's Independence Day and on his field theory.

April 18, aorta ruptures -- dies.

- His last words are in German and not understood by the American nurse.
- cremated in a small circle and the ash is scattered at an undisclosed place.
- His brains are preserved and investigated still under study (e.g. by FSU professor Dean Falk <u>http://deanfalk.com/scientific-articles/</u>)











From left: Unidentified woman; Albert Einstein's son, Hans Albert (in light suit); unidentified woman; Einstein's longtime secretary, Helen Dukas (in light coat); and friend Dr. Gustav Bucky (partially hidden behind Dukas) arriving at the Ewing Crematorium, Trenton, New Jersey, April 18, 1955.



Friends and family make their way to their cars after the funeral service for Albert Einstein, Trenton, April 1955. The ceremony was brief: Einstein's friend Otto Nathan, an economist at Princeton and co-executor of the Einstein estate, read some lines by the great German poet, Goethe. Immediately after the service, Einstein's remains were cremated.

Albert Einstein: the man of the 20th century?

- Unusually sharp wit.
- □ Unusually large perseverance.
- Unusually independent.
- □ Unusually versatile.
- □ Waiting for the new Einstein:
 - Unification of gravity with the other forces.
 - Dark matter and dark energy.
 - Explanation of the values of physical constants (k, h, e, c, me, mp, ...)
 - ...
- physics is still not finished!

□ Very humble:

- wrote in his book "The World as I See It" (publ. 1934, based on lectures at King's College, London, 1921):
- "Let every man be respected as an individual and no man idolized. It is an irony of fate that I myself have been the recipient of excessive admiration and respect from my fellows through no fault, and no merit, of my own. The cause of this may well be the desire, unattainable for many, to understand the one or two ideas to which I have with my feeble powers attained through ceaseless struggle."



Herb Block, New York Times, 19 April 1955

