General Relativity

aka "GR"





"'rinciple of equivalence"



Special Relativity

contained a problem

What about most of the universe...?

Where gravitation is a fact of life?

In particular...the action-at-a-distance thing.

Think about the tides...caused by Moon

closer, so stronger, high tide further, so weaker, low tide

That violates the rules of Special Relativity



Suppose Moon disappeared?

Would the tides flatten instantly?

what's worse

Masses appearing different from different frames?

How do you deal with Newton's Universal **Gravitational formula?**

distance?



Worrying about Gravity led Einstein to

think hard about

SPACE and TIME

moving coordinate systems

accelerating

5

the general theory of relativity

What's the "special" in "special" relativity?

the physics of inertial frames

What about the most obvious accelerating condition?

weight.

6

the questions

that stimulated General Relativity you can visualize







his journey

1907

"I was sitting in a chair in the patent office at Bern when all of a sudden a thought occurred to me. If a person falls freely, he will not feel his own weight."

painter? who knows...





stupid
elevator
trick, #1

gravitational attraction



gravitational force

stupid
elevator
trick, #2

gravitational attraction





force up to create an acceleration of 1*g*

Here comes a Relativity-like statement:

similar to Galileo's ship-hold...

"you can not perform any mechanical experiment to tell you that a ship is moving at constant speed relative to the land."

or Einstein's...

"you can not perform any mechanical or electromagnetic experiment to tell you that a ship is moving at constant speed relative to the land."

There is no mechanical or electromagnetic experiment elevator boy can perform

that would tell him that he was

1. being attracted by the Earth due to gravity or

2. being pulled and accelerated at g with no gravitational field anywhere

There is no mechanical or electromagnetic experiment he can perform

that would tell him that he was

1. being attracted by the Earth due to gravity or

2. being pulled **and accelerated** g with no gravitational field anywhere

said another way

any effect in an accelerated rest frame

should occur in a rest frame at rest in a gravitational field

called sometimes

weak Equivalence Principle

stupid elevator trick, #1 gravitational attraction

stupid elevator trick, #2 gravitational attraction



identical



subtle invention of the Equivalence P inciple

force down at g



gravitational force

EP says that if these are the same

the laws of physics will be identical

So, anything that happens in L happens in R and visa versa

 $F = G \frac{Mm(\text{grav})}{R^2}$

 $m(\text{grav}) \equiv m(\text{inertial})$

outer space



force up at g



inertial force

F = m(inertial)a



relative to couch people:

at rest

constant speed up





straight, slanted

CP observe light beam: horizontal

boy observes light beam: horizontal

horizontal

accelerated, up



accelerating frame

light appears to travel differently shaped paths between relatively accelerated frames

Then the Equivalence Principle requires:

light should also curve in the presence of gravity





Equivalence Principle messes with: "straight"

around a gravitating mass, the curve path is still:

"straight = shortest distance between two points"

best example: the path that a beam of light would take

But: straight in one frame is curved in another

from:

a new kind of "straight" ...a new appreciation for



light appears to travel differently shaped paths between relatively accelerated frames

Then the Equivalence Principle requires:

light should also curve in the presence of gravity





light paths

map the shape of space





20

not just light

acceleration also messes with geometry

straight is not straight

and Einstein knew that this was problematic $C=2\pi R$

experimentally: you could show that

Now, start it rotating.

fast...so special relativistic effects are apparent.

The ruler on the radius?

The rulers on the circumference?

 $C \neq 2\pi R$

The rules of Euclid's geometry – flat geometry – don't hold for an accelerating object.

Hold this thought: accelerated motion seems to change regular Geometry.



acceleration warps space

from the Equivalence Principle



gravity should warp space

light beam what about time? use a clock accelerating.... so light

so light to **B** is moving away from **A**



receives at say 5 ticks per second

1 second

B would say that A's clock has longer between ticks:

Runs Slower

sends at say 10 ticks per second

1 second

light beam

Equivalence Principle would

require that: B would say that in a gravitational field A's clock has longer between ticks:

it appears to Run Slower





"red shift" longer between ticks?

like the wavelength of the light is longer as seen by B than as seen by A



- Increasing Frequency (ν)

10 ⁸	10 ⁶	10^{4}	10^{2}	10^{0}	ν (Hz)
FM	AM	Ţ	ong radic	waves	
Radi	o waves	-	iong ruure	,	
10 ⁰	10^{2}	10^{1}	10^{6}	10^{8}	λ (m)

acceleration warps time

from the Equivalence Principle



gravity should warp time

free-fall.

is a strange state of motion

you don't notice your own weight





training in the Vomit Comet KC 135





free fall is special light mus free-fall in bend in the another Equivalence Principle Neither situation "sees" gravity you can "transform" gravity away

deep spage Einsteppace

no gravity no gravity





The Equivalence Principle demands that

If some phenomenon happens in one circumstance,

then it must happen in the other one.

circumstance, her one.

IMO modeling this for the first time was

the most technically challenging piece of physics ever

Hilly 105. $\frac{d}{dt} \cdot 2\dot{f} = -\int \sigma \frac{\dot{s}}{2\pi} = -\int \sigma \frac{d}{dt} \left(\frac{t}{2}\right)$ $2\dot{f} = \int \sigma \cdot \frac{t}{2\pi} + C$ Fine Die Burgungs gleichungen me mohenillen Tweekles landen : $J_{s} = (\tilde{R}_{s} \quad \text{also} \quad (bei \ ue \ e): \quad -\frac{d}{dt} \frac{g_{s} \dot{x}_{s}_{s} \dots + g_{rs}}{ds} = -\frac{i}{2} \sum_{\mu \nu} \frac{\partial g_{s}}{\partial s}$ thorque 1/2 12 auf Dos Reptorat ! E= c, (1-2 =+2 ==) -12 4= 22 E=1-1 + 12 . Na hen je ige low : Gen dawnsher i die Aborily a 6 = + In (qu, dx. + ... + quy dxy) ales: E = - gr dt 2 Ester Angl 4 (T + x2 1) Perile (burgers , be ally ka pa ka : C.E . 20:-0: 4 + 2" 2'd q + da' = 2 c. E - 2 c. + C. A Datie ist (and floor S. 6 +, and S.7 gl. 5), w de Coming I und m 2: Billiebo mendlich Alein er 2"dy 2: (Jo : de + C)'de N = do . /g. x + . + . + 2 $\frac{d^{2}T}{dx^{2}} = \frac{1}{r}\frac{dT}{dr} + x^{2} \cdot \frac{1}{r}\frac{d}{dr} \left(\frac{1}{r}\frac{dT}{dr}\right)$ = $\frac{\frac{1}{2}}{\frac{1}{2}} \frac{2}{\frac{1}{2}} \frac{1}{\frac{1}{2}} \frac{1}{\frac{$ 9 ... Bw $U = -g_{vv} \frac{dt}{ds} = -g_{vv} / \frac{1}{2s_{c}^{2} \cdot 2s_{v}^{2} s_{1}^{2}} \frac{1}{2^{4}} dy^{2} = (\int_{\sigma} \frac{1}{2} + C)^{2} (2^{2} dy^{2} + dz^{2})$ $\Delta T = \frac{3}{r} \frac{dT}{dr} + \frac{1}{r} \frac{d}{dr} \left(\frac{1}{r} \frac{dT}{dr} \right)$ $dt \left[\frac{2c_0(\delta - c_0)}{+c_1^* A} \right]^2 dy^* = (J_0 + C_2)^2 dy^* = (J_0 - \frac{1}{2} + C_0)^2 dx^*$ und him keidligt Dess sich am Filde unt Du Best wich Eyz' = 39 ... $\frac{\frac{2}{2x}(x^2\frac{N}{r^2})}{2x(x^2\frac{N}{r^2})} = 2x\frac{N}{r^2} + x^3 \cdot \frac{1}{r}\frac{d}{dr}\left(\frac{N}{r^2}\right)$ 2 x dr (+ the Godalle with Juse Wer : O ge sign sind , were auch wide for x, = x , x = y $dp = \frac{\int_{-\pi} \frac{1}{2} \cdot \mathcal{C}}{\sqrt{t_0 [2(\delta \tau_0) + \frac{1}{2\delta}] \cdot 2^{\frac{1}{2}} - (S_0 + \mathcal{C}_2)^2}} dt$ W du - 1-9' + C. $\frac{2^{2}}{2x^{2}} = 2 \frac{W}{r^{2}} + 5 x^{2} \cdot \frac{1}{r} \frac{d}{dr} \left(\frac{W}{r^{2}} \right) + x^{4} \cdot \frac{1}{r} \frac{d}{dr} \left(\frac{1}{r} \frac{d}{dr} \left(\frac{N}{r^{2}} \right) \right)$ y'z' = B' (co - q' - co + n co + Die group and also , his and weadle the worde Owing (at 1-d. c. (1-d+ + d') = c. (1-24 2 = x2y. 1 d (N/r2) day due - Taga (6-G) $q^{2} = c_{0}^{*} \left(1 - \frac{d}{2} + h \frac{d}{2^{*}}\right) - \frac{c_{0}}{f^{*}} \left(1 - 2 \frac{d}{2} + \frac{f^{2}}{2}\right)$ gry = Col (1 - it + 3 12) Dela whereint and De glaren & $= x^{2} \cdot \frac{1}{r} \frac{d}{dr} \left(\frac{M}{r^{2}} \right) + x^{2} y^{2} \cdot \frac{1}{r} \frac{d}{dr} \left(\frac{1}{r} \frac{d}{dr} \frac{g(M)}{r^{2}} \right)$ $\frac{dt^{*} + t^{*} dy}{dt^{*}} = C_{0}^{*} \left[1 - \frac{C_{0}^{*}}{C_{0}} + \frac{d}{2} \left(2 \frac{C_{0}^{*}}{L^{*}} - 1 \right) + \frac{d^{*}}{2} \left[m - \frac{C_{0}^{*}}{C_{0}} \right]$ $\Delta(x^{2}\frac{N}{r^{2}}) = 2\frac{N}{r^{2}} + \int_{0}^{\infty} x^{2}\frac{1}{r}\frac{d}{dr}\binom{N}{r^{2}} + x^{2}\frac{1}{r}\frac{d}{dr}\binom{1}{r}\frac{d}{dr}\binom{1}{r}\frac{d}{dr}\binom{1}{r}$ $\frac{dt}{dt} \frac{\partial t}{\partial t} = -\frac{1}{2} \frac{\partial t}{\partial t} \frac{\partial t}{\partial t} \frac{\partial t}{\partial t} \frac{dt}{dt} \frac{dt}{dt} = -\frac{1}{2} \frac{\partial t}{\partial t} \frac{\partial t}{\partial t} \frac{\partial t}{\partial t} = -\frac{1}{2} \frac{\partial t}{\partial t} \frac{\partial t}{\partial t} = -\frac{1}{2} \frac{\partial t}{\partial t} \frac{\partial t}{\partial t} + \frac{\partial t}{\partial t} + \frac{\partial t}{\partial t} \frac{\partial t}{\partial t} + \frac{$ $\frac{3}{r}\frac{dT}{dr} + \frac{1}{r}\frac{d}{r}\left(\frac{i}{r}\frac{dT}{dr}\right) + 2\frac{N}{r^2} + x^2\beta \frac{1}{r}\frac{d}{dr}\left(\frac{d}{r}\right)$ $\int \frac{dL}{(1+x'_{2})} \frac{dL}{(1-z'_{1})(2-z')(2-z'')}$ $= \frac{2\pi}{\sqrt{2}\sqrt{2}} \left\{ 1 + \frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) \left(\alpha + \frac{2^{\prime} + 2^{\prime}}{2} \right) \right\}$ H $\int_{-\infty}^{\infty} \frac{d^2}{dz} \left[dz^2 + z^2 dy^2 \right] \left(1 - 2\frac{d}{2} - \rho \cos \frac{d^2}{2z} \right) = \int_{0}^{\infty} z^2 dy^2 = L +$ 2'+2"= - J+ & / C = - J. - #2 1 + + + + 2 d2' (() (1-2' - popl') = dy = jor's [. $+2, +2, +2'+2'' = \frac{A}{2z(c_{*}-b)}$, $2, +2z = \frac{A}{2z(c_{*}-b)} + \frac{A}{C}$ + 1/2 (1 1/4 - x 1/6 dr 60 6 (1-2 + 120) 1,2, = 1- 2 02"+ A (21+1) 4 2 3- [A" (n+1) $\alpha \varphi = \frac{\mathcal{B}}{\delta l \overline{\epsilon}} \int \frac{1}{\sqrt{-z^2 + (\frac{1}{\epsilon} + z)} d z^2 - \frac{1}{\epsilon} \tilde{\omega} \frac{\partial}{\delta}}$ $-(1+\frac{1}{2}d^{+}\frac{y^{+}}{2}-\frac{1}{2}d^{+}\frac{1}{2})$ dr() = - 1 1 6 de (ENCO) 71 1=-14 - 3 + + + + + + - 5 + + died abed De yuster Vingla = 2. 2. perfi . Si beto klan L'and 2" 1=34 -1+L Inhormant more 2'+2 2 2 A E (1+0A) = ((1-2) , 2,+22 = ÷ (1+ 1) $2_{1}2_{1} = \frac{1}{E}\left[k(\frac{1}{E}) + (n+1)A\right] - \frac{1}{E}A = \frac{1}{E}\left[(\frac{1}{E})^{2} + (n-1)A\right]$ $\frac{1}{2} \int \frac{1}{2\pi} \frac{1}{2\pi} \int \frac$ + (+ 3 + + 2) (+1

the question became:

Could gravity be an illusion?

A circumstance relative only to your state of motion?

Could gravity be "transformed away"

by the change of a reference frame?

Maybe gravity is not a force at all?

there should be observable consequences

and Einstein knew it

and calculated them - half a decade of Newton-like concentration

what we've found:



gravitating bodies...masses:

warp both space and time.

They warp: spacetime

Einstein had to learn that geometry & <u>energy-mass</u>

interact & that space and time respond

After his "happy thought": 5 years for him to figure it out



he had to go back to school...privately with his buddy Marcel Grossman





tests of general relativity

There are a handful of "classic tests"

of these ideas:

that space and time are warped by gravitation



light beam what about time?



В

use a clock Gravitational Red Shift is built so B moving away from A A and B under Orevitour phone ScGaPSger inertial frames at each ifiyou get where you want to go you just confirmed General Relativity per second

force up at g



receives at say 5 ticks per second

1 second

"Advance of the Perihelion of the Orbit of Mercury"

Vulcan?

Mercury

misbehaves

"advance of the perihelion"

Einstein calculated it including the sun's warping of space



1916: Got precisely the right amount.

Heart palpitations when he scribbled the result on his paper...

point of closest approach of the orbit advances by 43 seconds of arc per century

the mother of all experiments

the "solar eclipse" experiment

Google solar eclips All Vide

About 6,480,0

Videos

Solar eclip experiment

KSDK News YouTube - Aug

People al

What is th What fam Who prov How can

A Picture-

Nature: Total

Solar Eclipse Model I Science project I Education.com https://www.education.com > Entire library > Science projects > First Grade > Science * Check out this fun science fair project idea for 1st grade: a solar eclipse model that demonstrates total, ... In this experiment, you'll use an apple as the sun.

se experiment				Q
os Images	News Shopping	More	Settings	Tools
000 results (0.49 se	econds)			
	sp	1	1	T.
	STRIC	*		
2:08		6:43	You'll need: 2 bails and a flas	hlight 0:49
se ts	Astronomy 4 Kids	: So for	iar Eclipse Acti Kids	vity >
	eclipses			
18 2017	Astronomy4Kids	Tris 5 You	sha Stanley Tube - Aug 1, 2017	
lso ask				
ne solar eclips	e experiment?			~
ous theory wa	as proven during tl	he 1919?		~
ved Einstein's	theory of relativity	?		~
l see a solar e	eclipse?			~
			I	Feedback
-Perfect Solar	Folipse Experime	ent - Sky & Te	lescope	
i oneol oola				

https://www.skyandtelescope.com/...news/a-picture-perfect-solar-eclipse-experiment/ -Feb 16, 2018 - In the August 2016 issue of Sky & Telescope, I explained that I was going to set up an experiment to measure the gravitational deflection of ...

How a Total Solar Eclipse Helped Prove Einstein Right About ... https://www.space.com/37018-solar-eclipse-proved-einstein-relativity-right.html 🔻

May 29, 2017 - The event will be a great opportunity to revisit a groundbreaking experiment that occurred during a total solar eclipse, and helped confirm Albert ...

Solar eclipse of May 29, 1919 - Wikipedia

https://en.wikipedia.org/wiki/Solar_eclipse_of_May_29,_1919 -

A total solar eclipse occurred on May 29, 1919. With the duration of totality at maximum eclipse of 6 minutes 51 seconds, it was the longest solar eclipse since ...

Greatest eclipse: 13:08:55 Duration: 411 sec (6 m 51 s) Max. width of band: 244 km (152 mi)

The Solar Eclipse and Eddington's Experiment - Department of Physics

https://www.cmu.edu/physics/news-events/news-archive/.../eclipse-eddington.html -Aug 15, 2017 - At 1:45 on Monday afternoon, August 21, the moon will begin blocking the light coming to us from the Sun. Over the next half hour, the skies will ...

"Solar Eclipse Experiment"



light

obeys the strong Equivalence Principle

the laser pointer...for real

The star is actually at A

Zariel. 14. X. 13. Each quelester Hers Kollege! time surfache theoretische Ufer legung market die Annahmes plausitel, dass Lichtstrahlen in einem Geavitation felde eine Deviation uphren. 15 Lechrebahl An Somencande misste diese Ablenkung (R Stationada and mil 1 abuchunen 50.84 To ware deshall von grösstem Interesse, bis que une grosses Sommen whe fills Firsteine bei turendung der stänkesten Vergrösserungere bei Tage (ohne Somenfinsternis) gerehen werden komun

1911 calculation – initially wrong, only the E=mc² component...

In 1915 he changed his 1911 calculation to include the warping of space...worth x2

The deflection should be about 1/4 milli-degree

