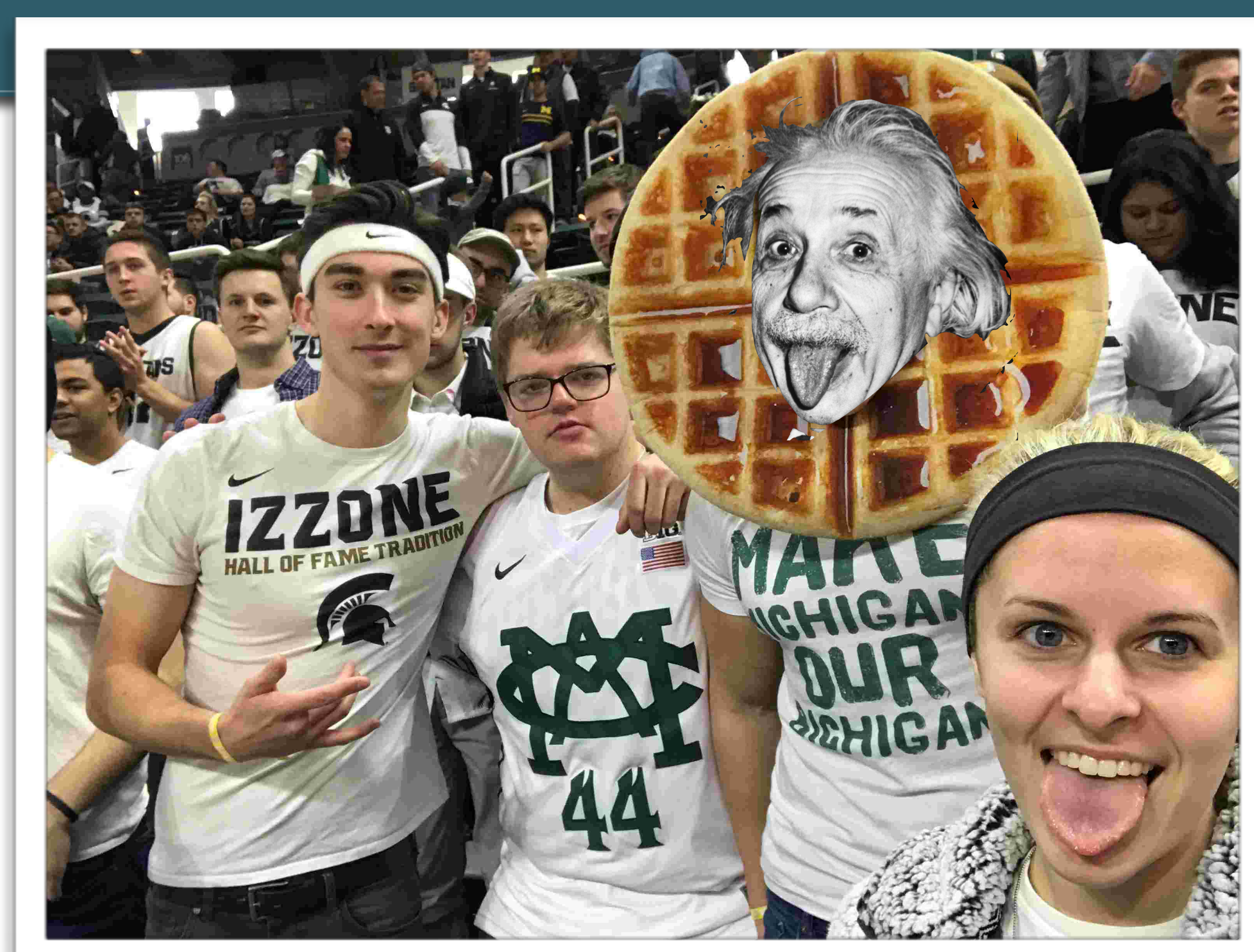
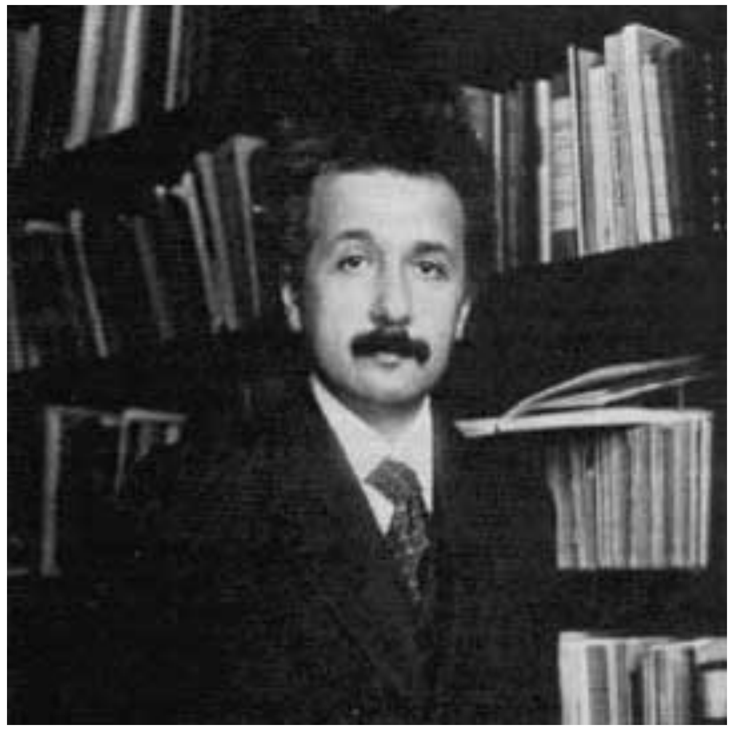
General Relativity

aka “GR”



‘‘principle of equivalence’’



Special Relativity

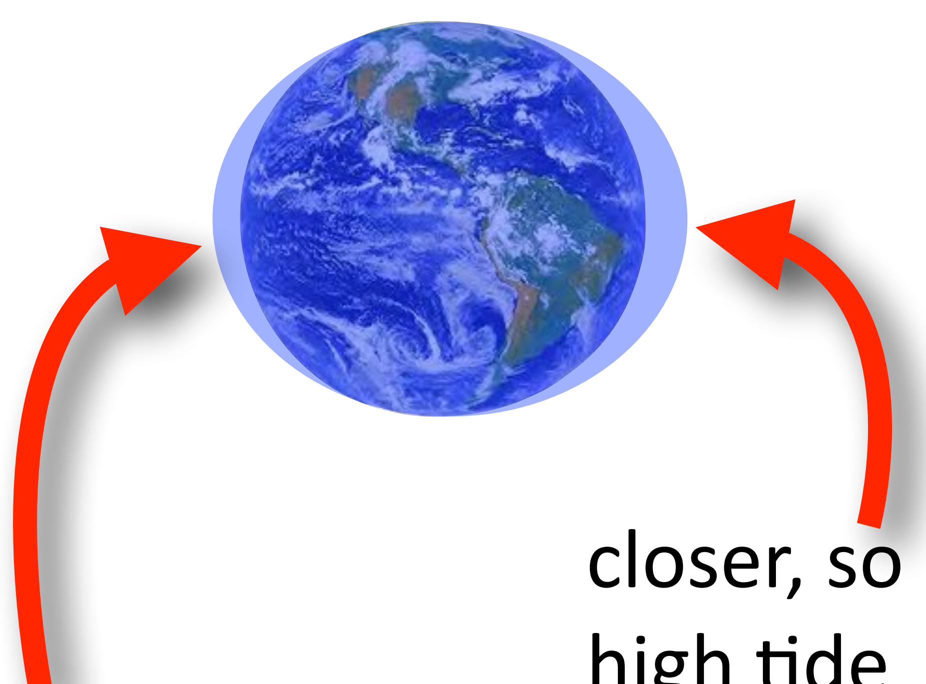
contained a problem

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

Suppose Moon disappeared?

Would the tides flatten instantly?

That violates the rules of Special Relativity

what's worse

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

Masses appearing different from different frames?

$$F_{1,2} = G\frac{M_1 M_2}{R^2}$$

Start length-contracting the distance?

Worrying about Gravity led Einstein to

think hard about

SPACE and TIME

~~moving~~ coordinate systems

accelerating

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.

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."

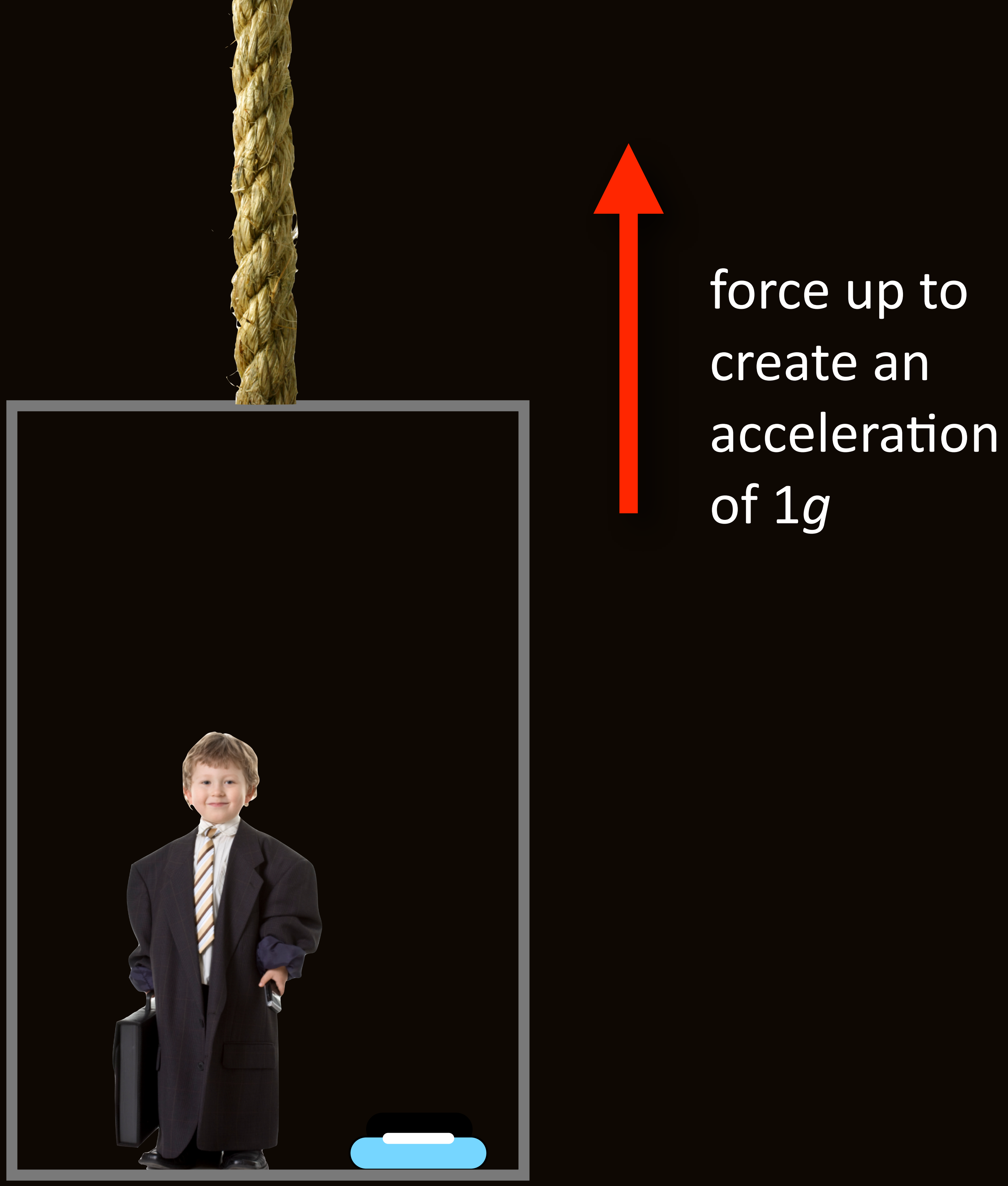
painter? who knows...

stupid elevator trick, #1

gravitational attraction

stupid elevator trick, #2

gravitational attraction



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...

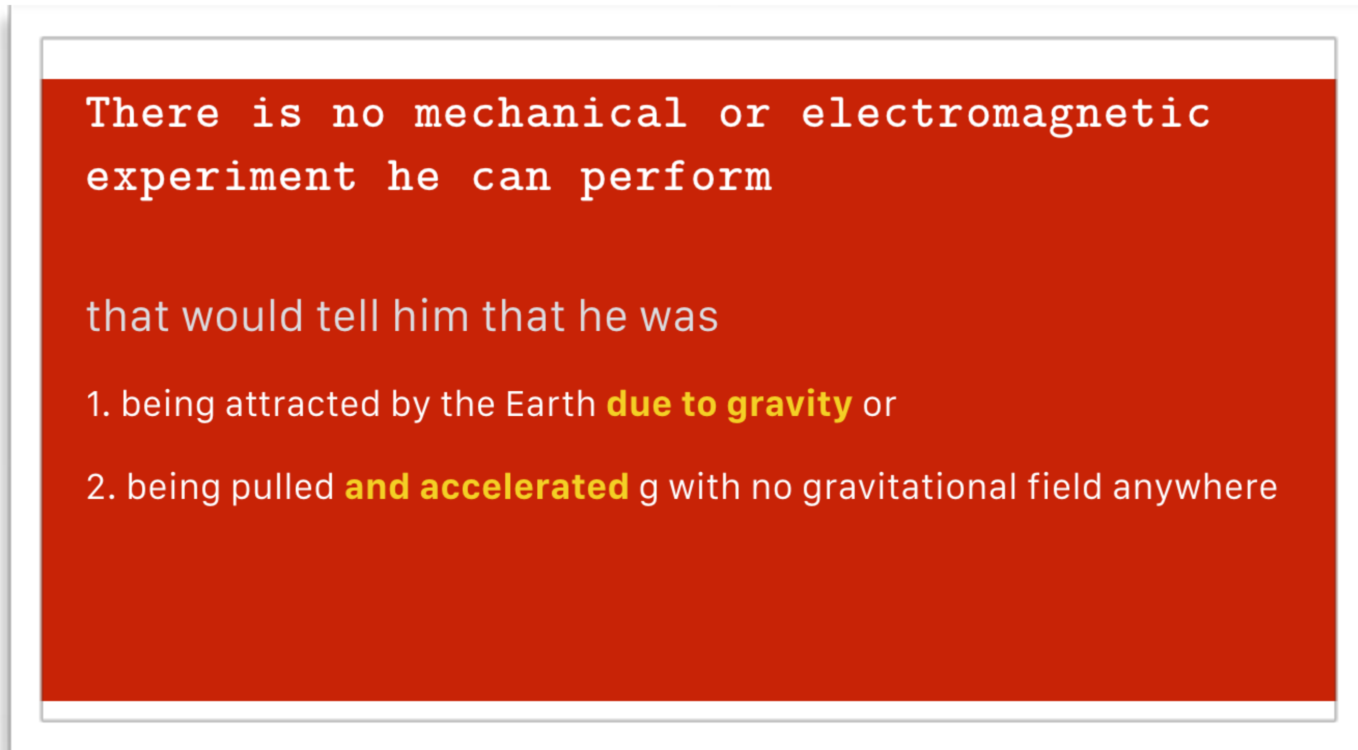
“you can not perform any mechanical or electromagnetic experiment to tell you that a ship is moving at constant speed relative to the land.”

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



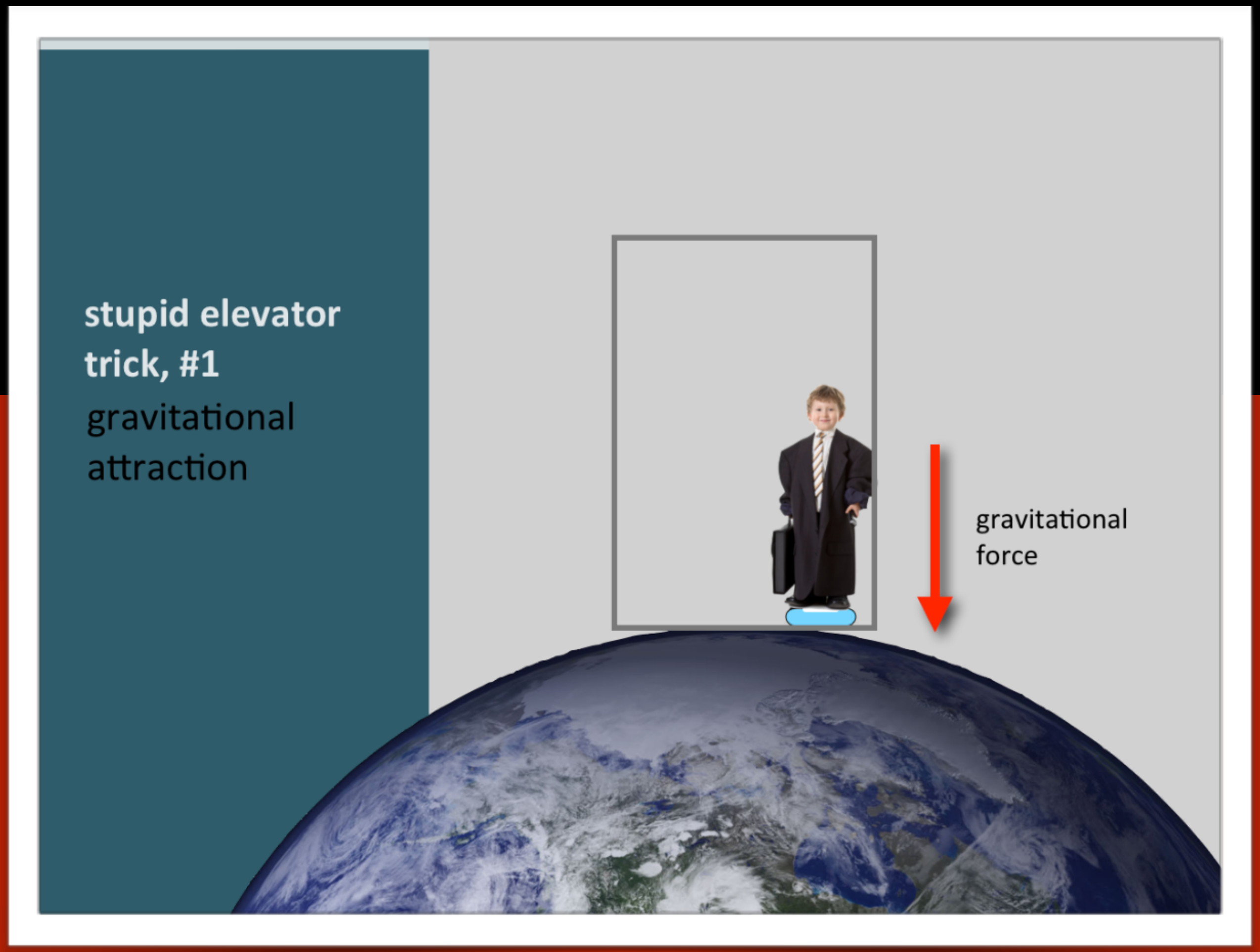
said another way

any effect in an accelerated rest frame

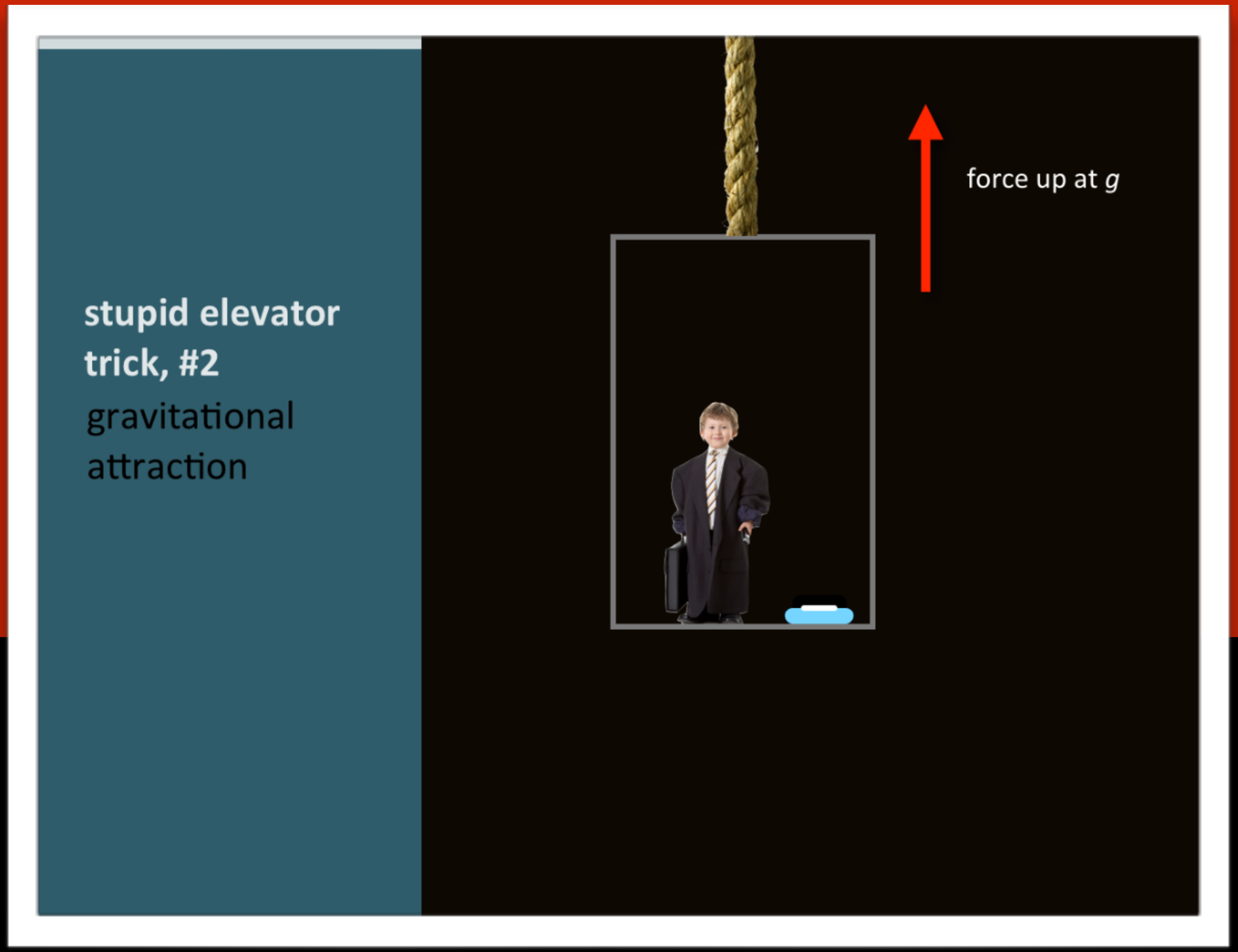
should occur in a rest frame at rest in a gravitational field

called sometimes

weak Equivalence Principle



identical



subtle invention of the Equivalence Principle

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

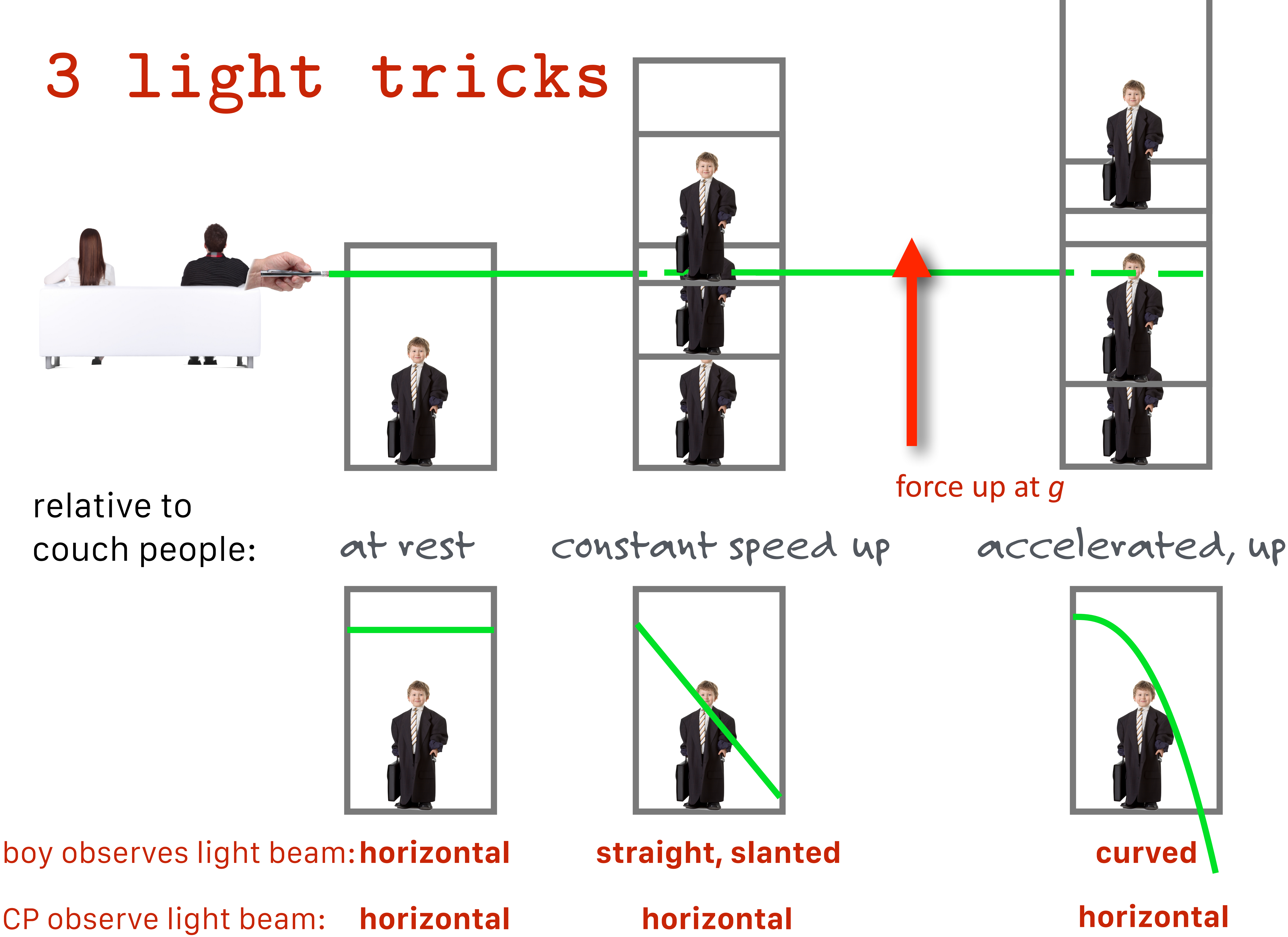
inertial force

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

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

$$F = m(\text{inertial})a$$

3 light tricks

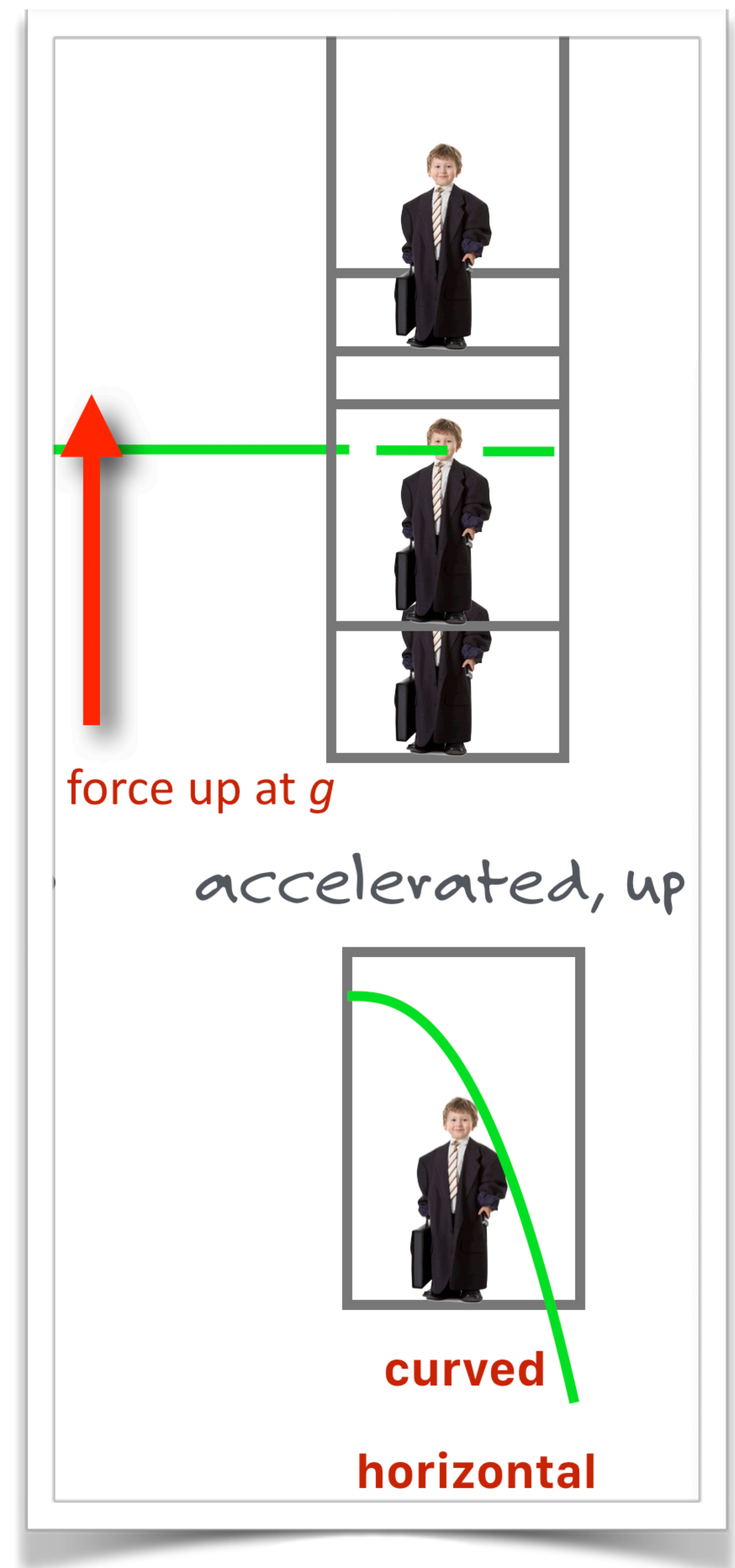


accelerating frame

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"

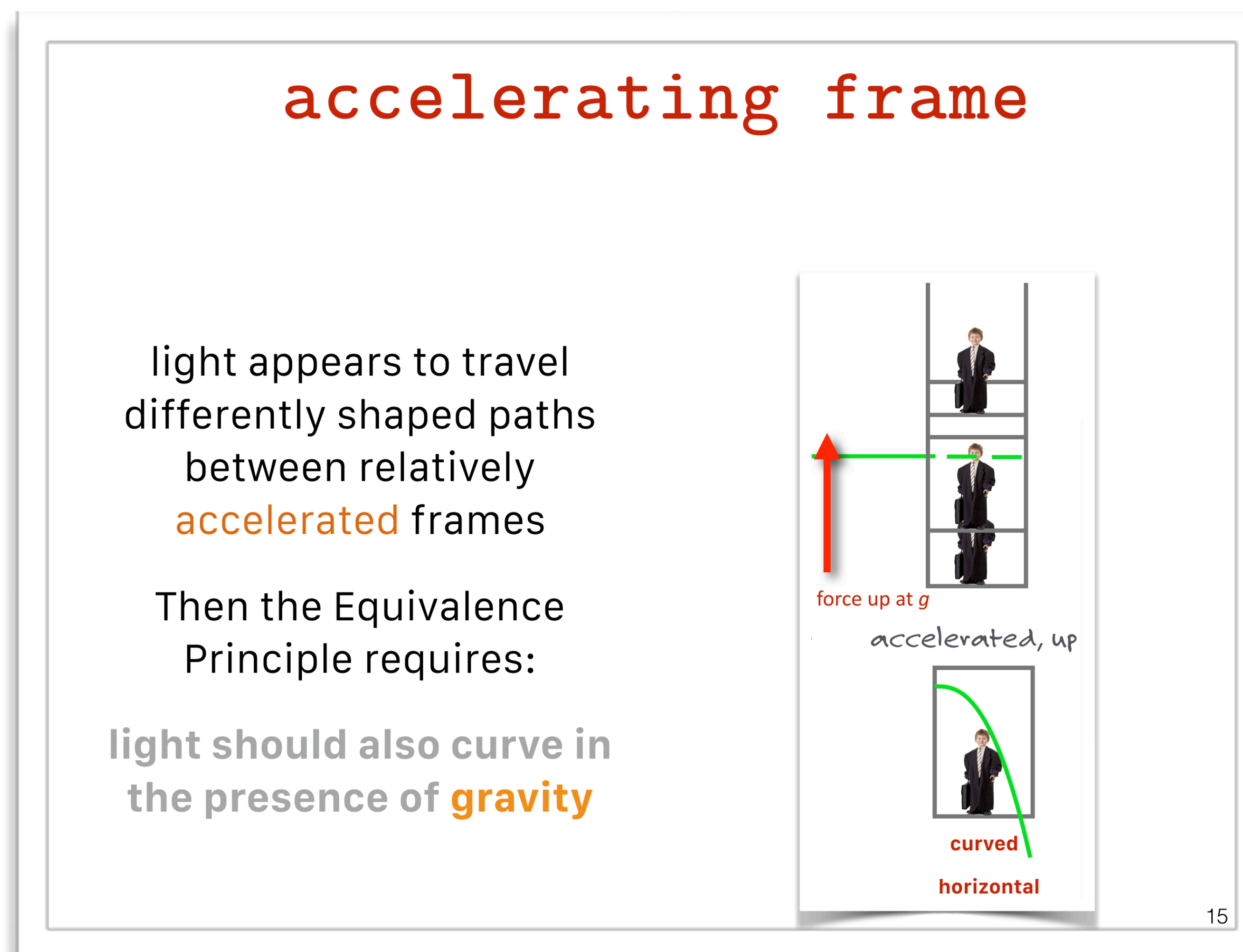
around a gravitating mass, the curve path is still:

"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

geometry

light paths

map the shape of space

geometry

not just light

acceleration also **messes with geometry**

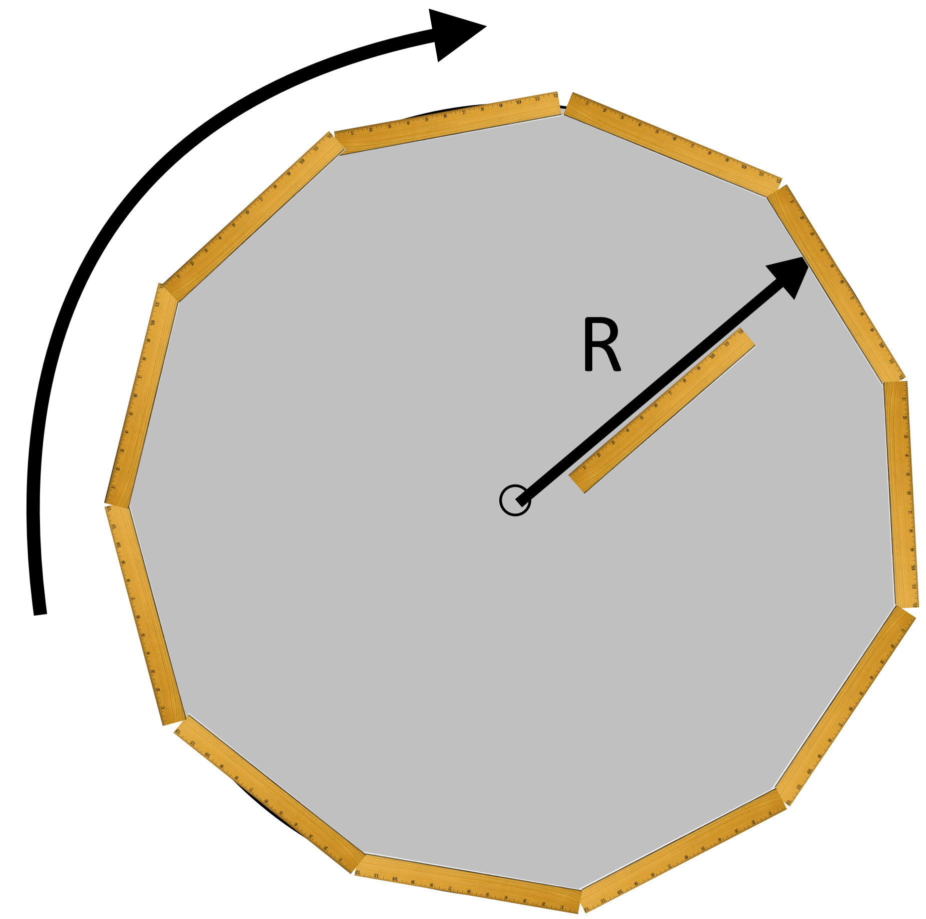
straight is not straight

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

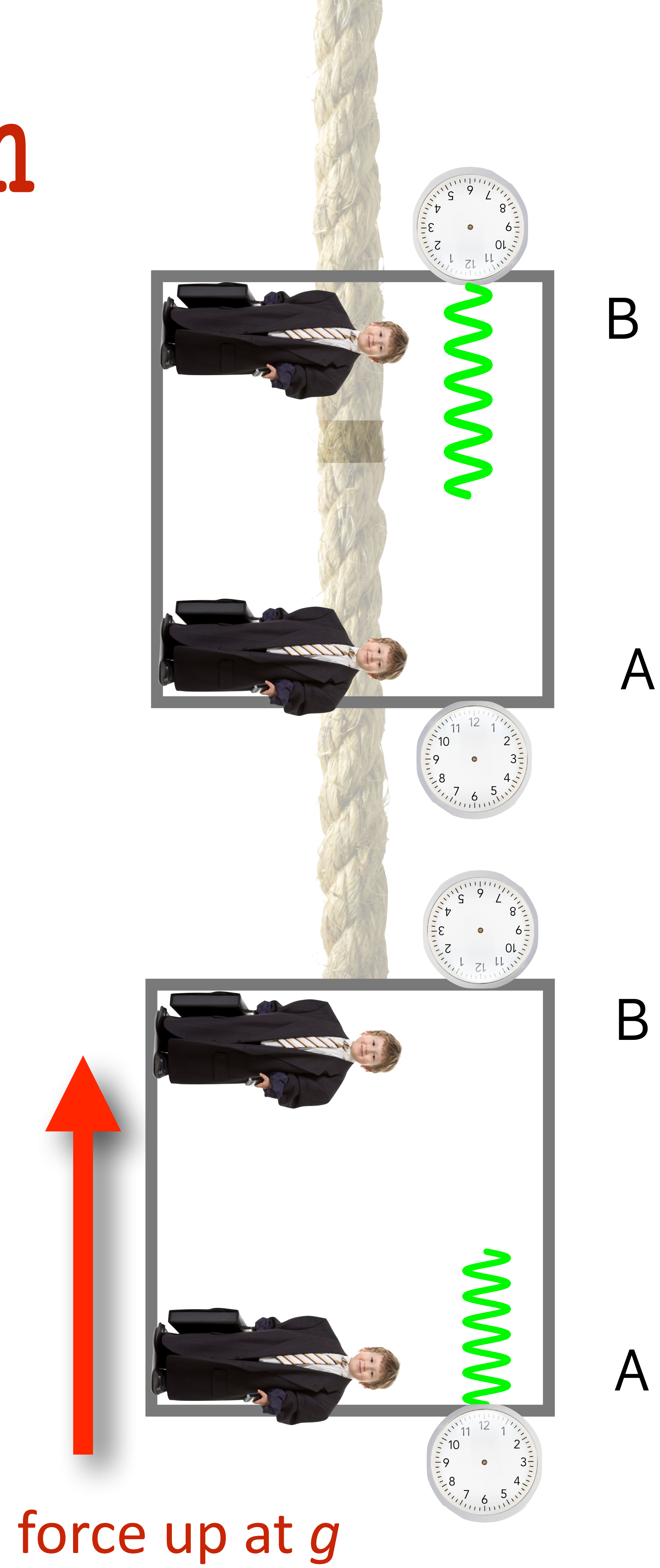
gravity
should
warp space

light beam

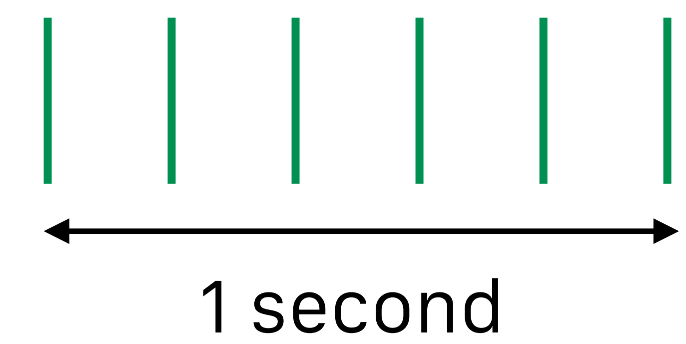
what about time?

use a clock

accelerating….
so light
to **B**
is moving away
from **A**



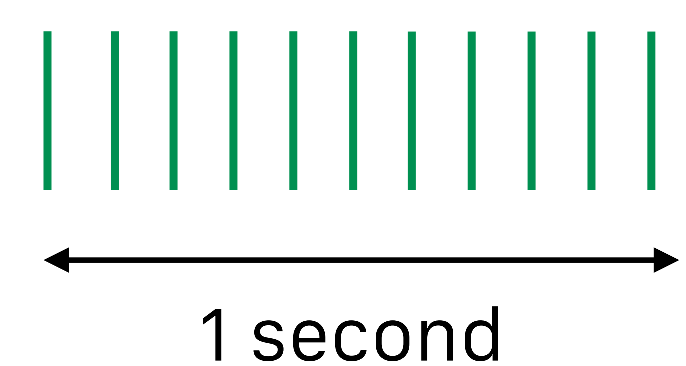
receives at say 5 ticks per second



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

Runs Slower

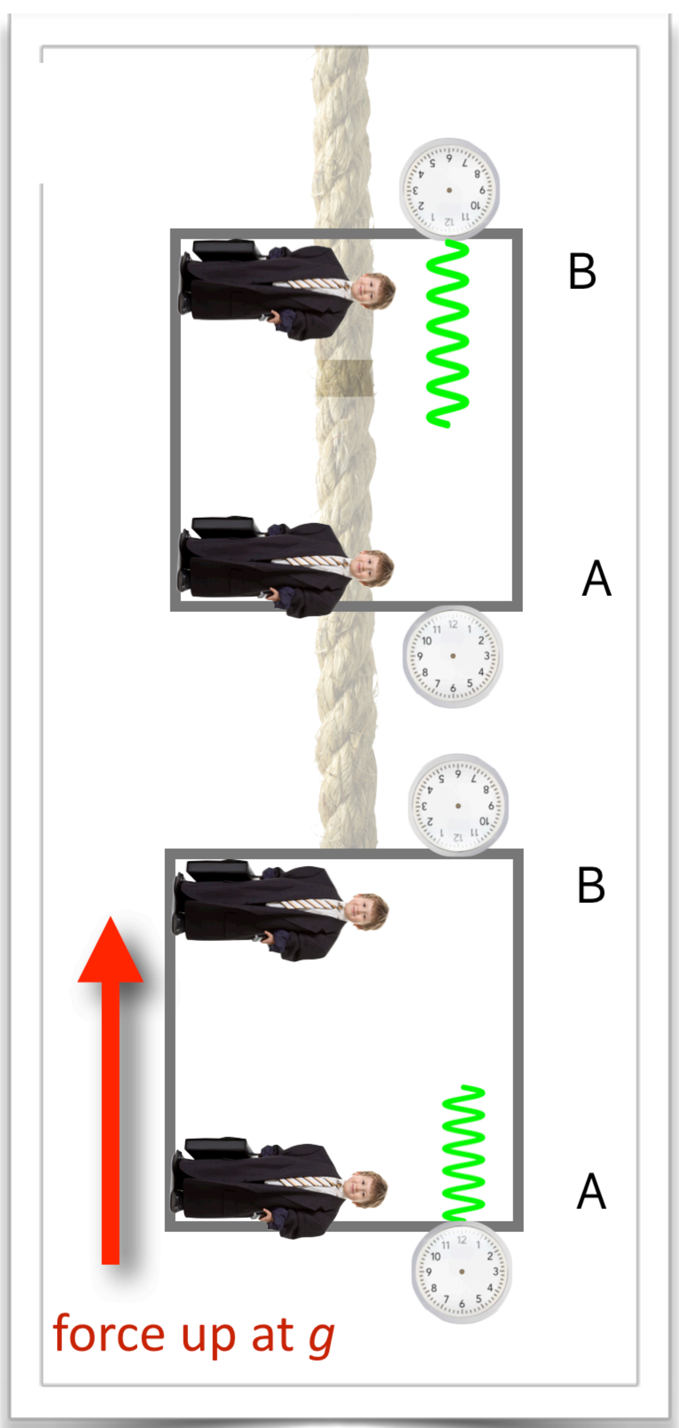
sends at say 10 ticks per second



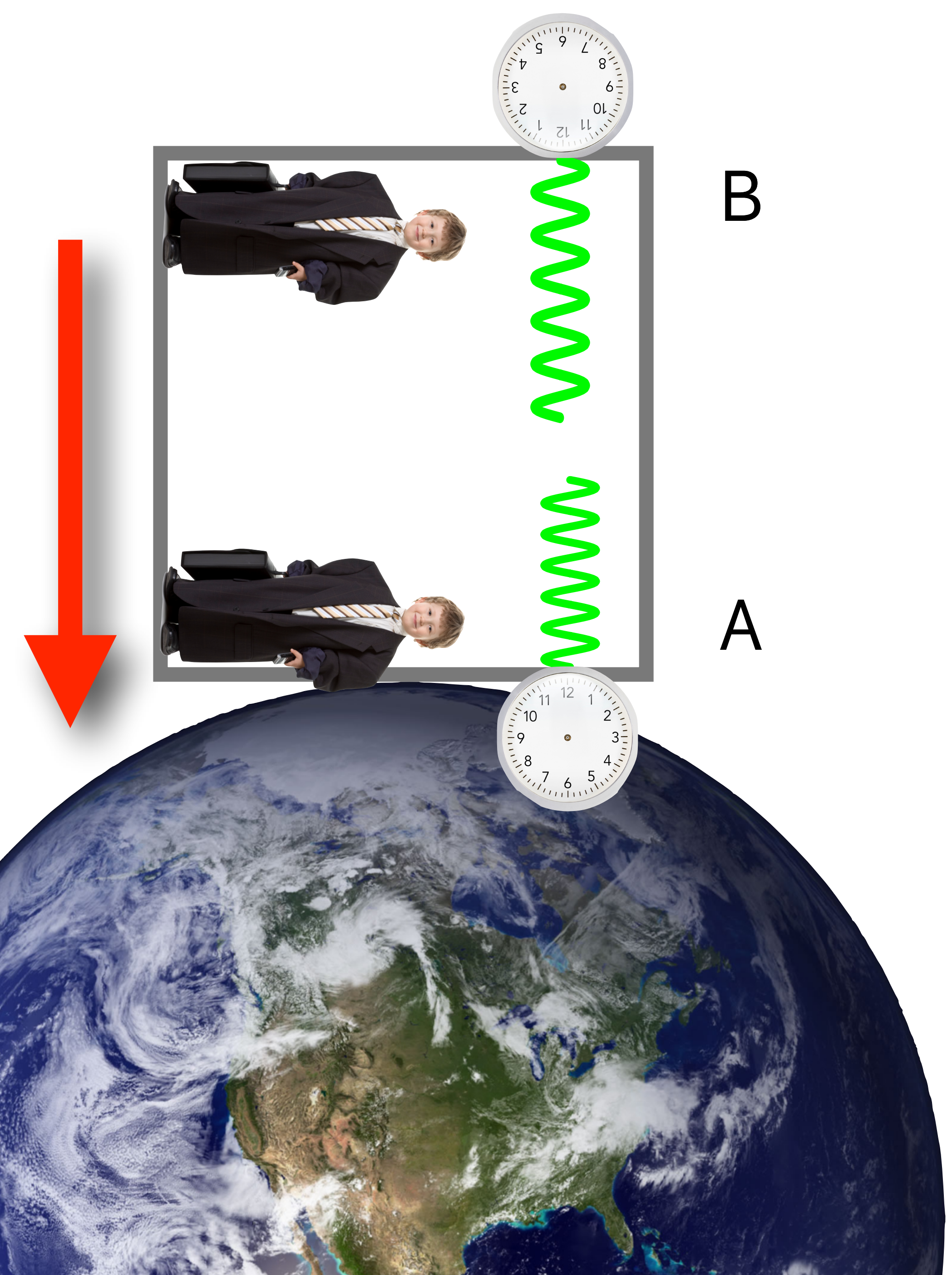
light beam

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



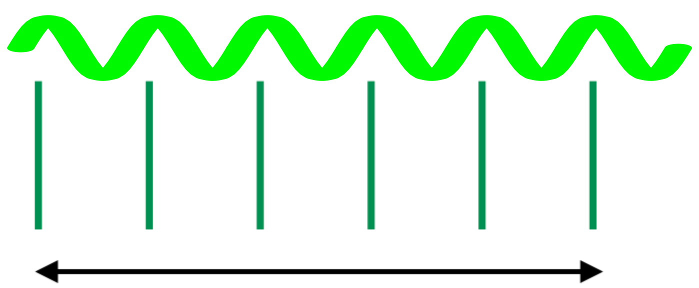
= force down at *g*



"red shift"

longer wavelength

receives at say 5 ticks per second

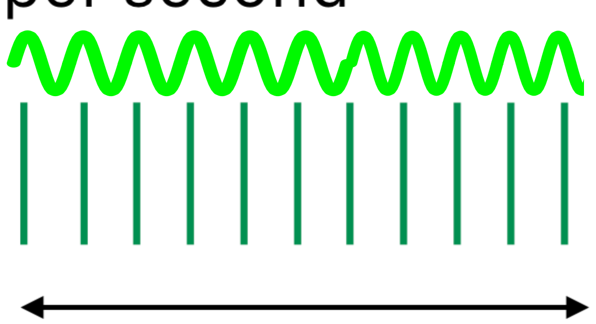


1 second

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

Runs Slower

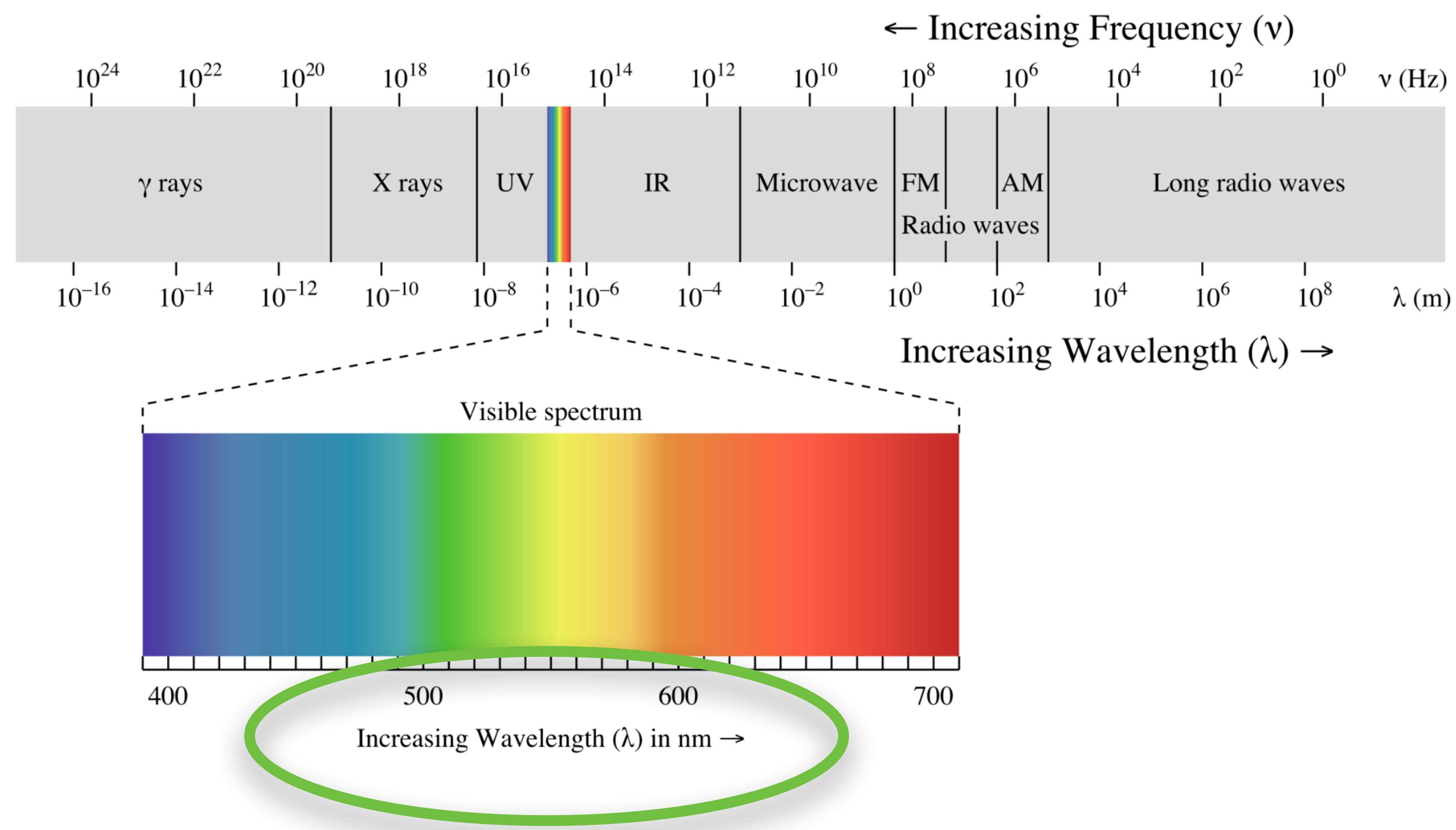
sends at say 10 ticks per second



1 second

longer between ticks?

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



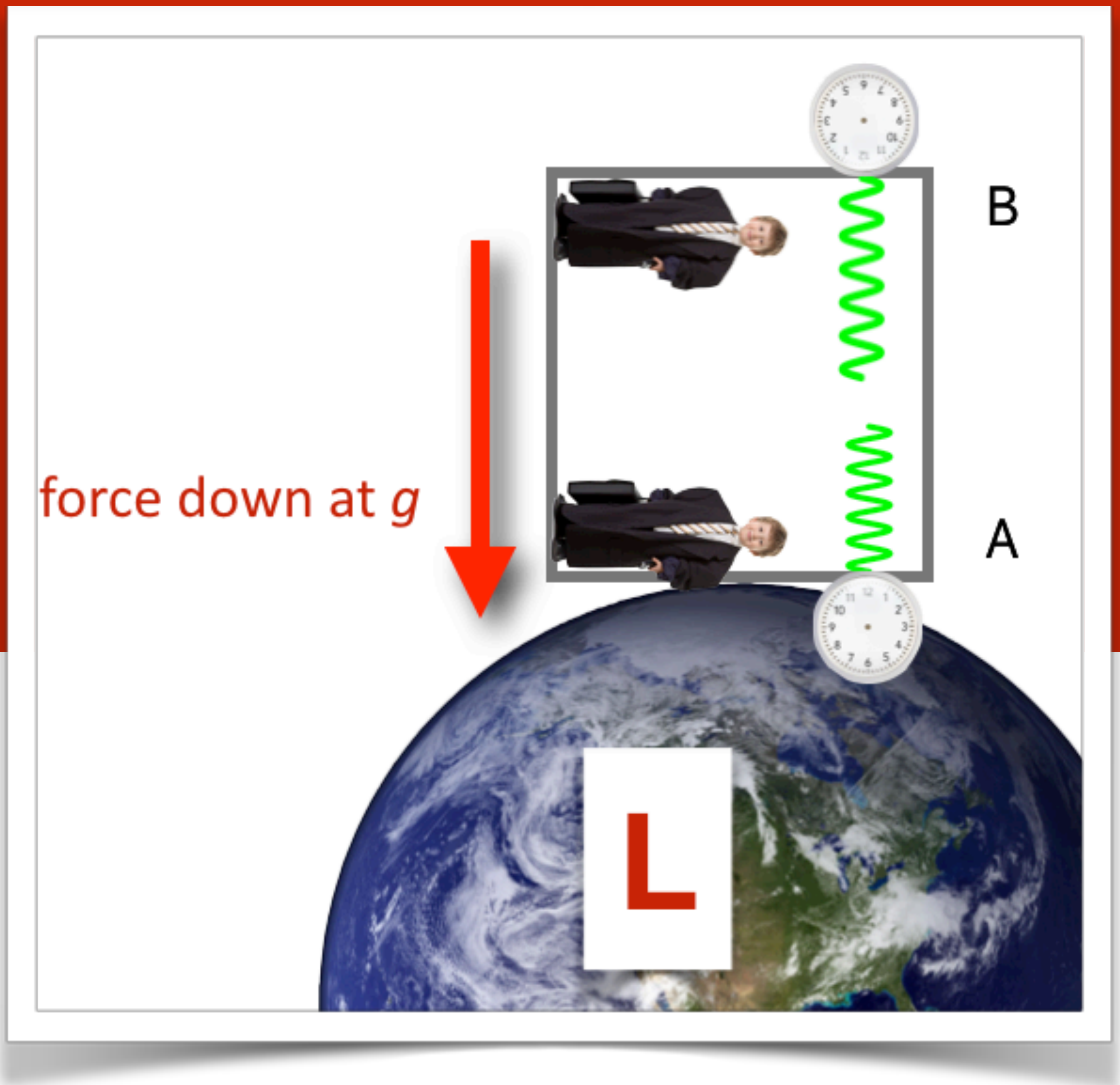
an apparent shift to

- a longer wavelength... "red shift"
- and a slower clock

acceleration
warps time

from the Equivalence Principle

gravity
should
warp time



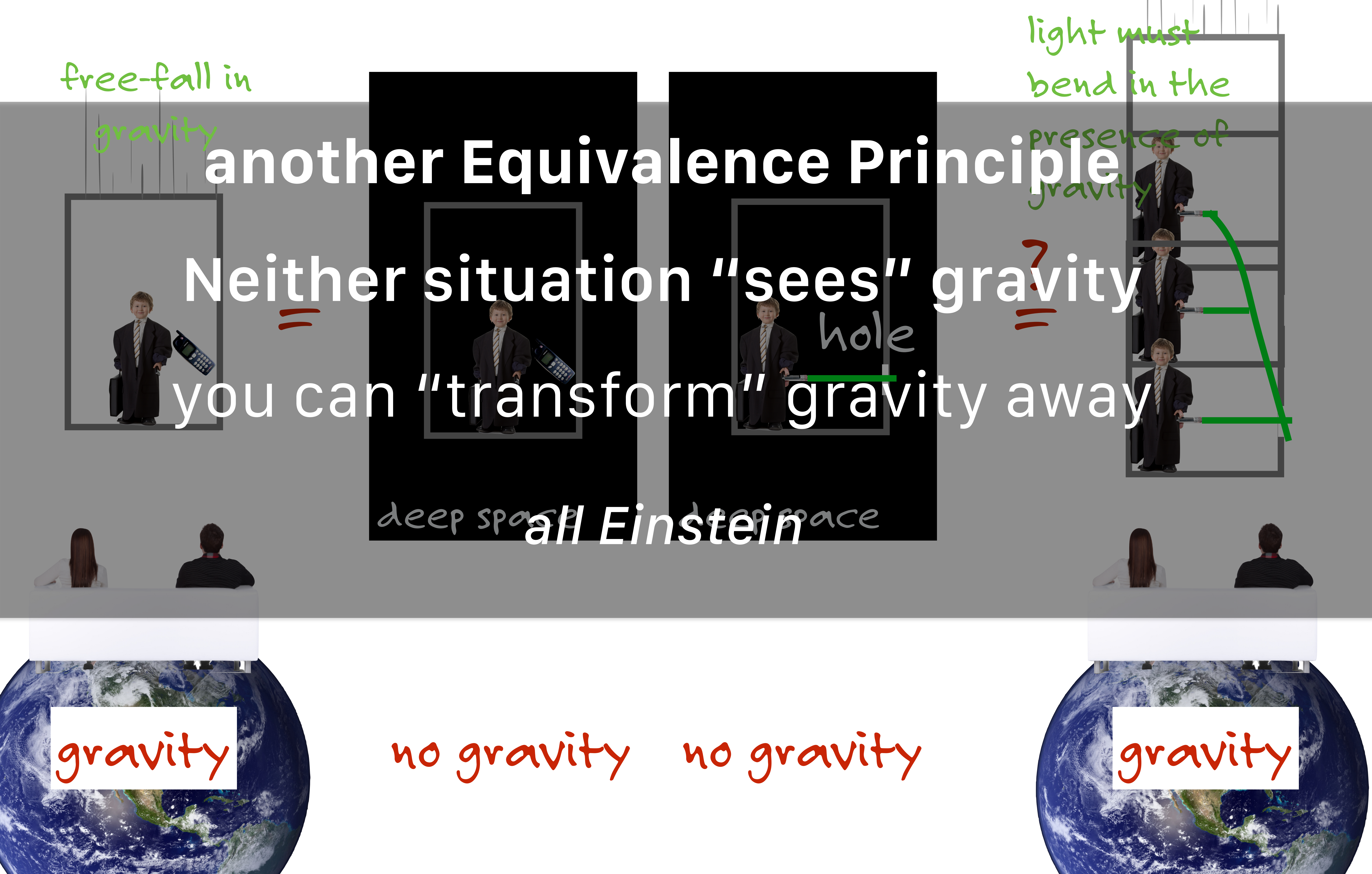
free-fall.

is a strange state of motion

you don't notice your own weight

training in the Vomit Comet KC 135

free fall is special



another Equivalence Principle

Neither situation "sees" gravity

you can "transform" gravity away

all Einstein

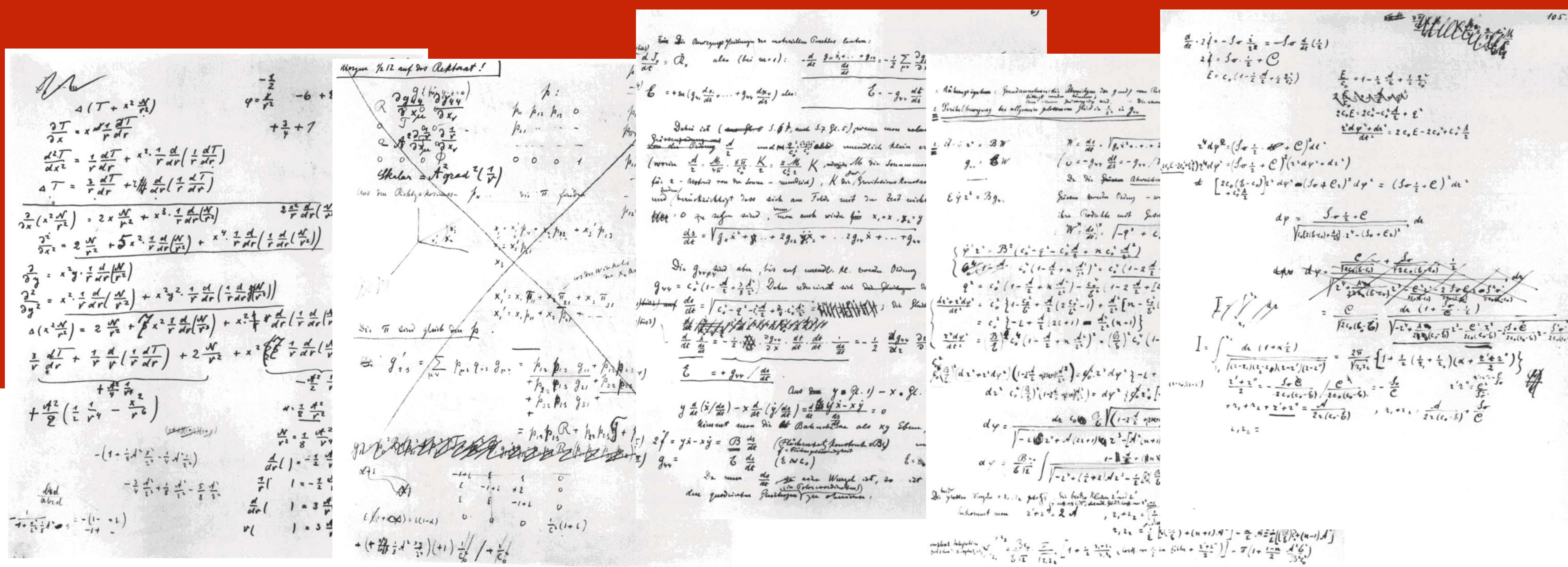
The Equivalence Principle demands that

If some phenomenon happens in one circumstance,

then it must happen in the other one.

IMO modeling this for the first time was

the most technically challenging piece of physics ever



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?

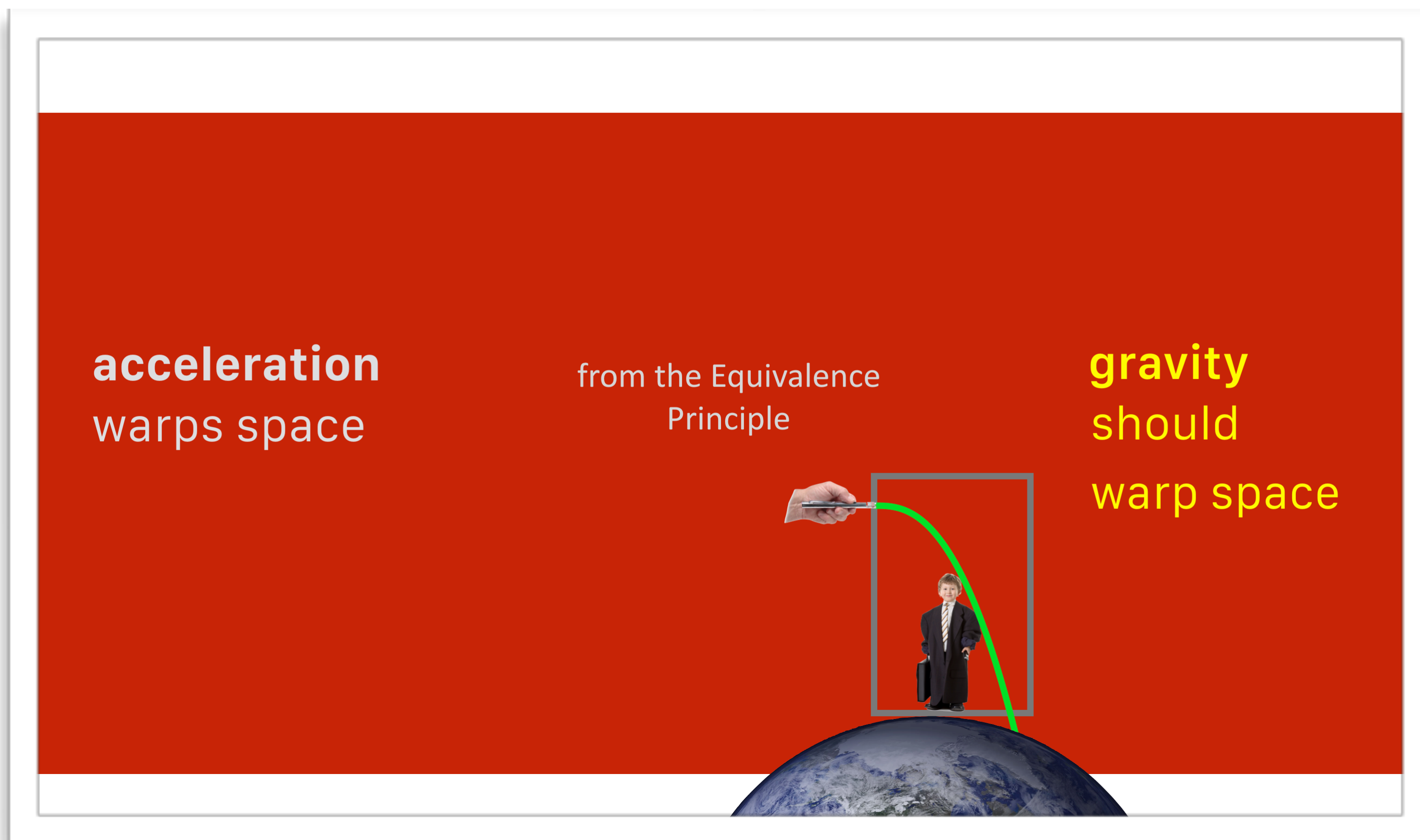
Maybe gravity is not a force at all?

there should be observable consequences

and Einstein knew it

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

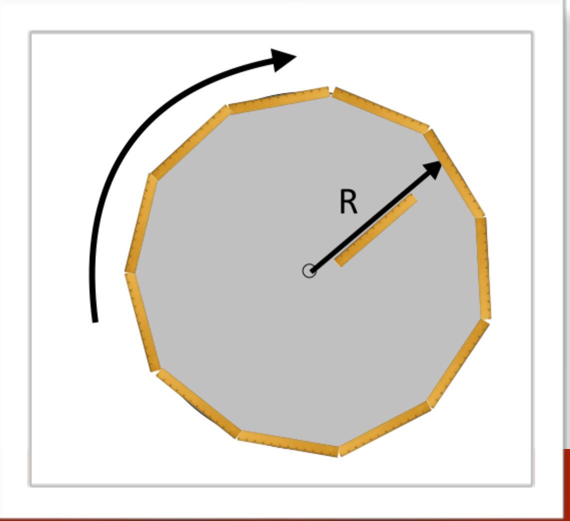
what we've found:



`gravitating bodies…masses:`

warp both space and time.

They warp: **spacetime**



<u>Einstein had to learn that geometry & 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

- Pound Rebka Gravitational Red Shift
- The perihelion of Mercury’s Orbit
- Light bending around the Sun
- “Gravitational Lensing”
- “The Hafele-Keating experiment”
- “Binary Pulsar period”
- Black Holes

light beam

what about time?

use a clock

accelerating....

so **B** moving away from **A**

A and B are different inertial frames at each time

Gravitational Red Shift is built into your phone's GPS

if you get where you want to go, you just confirmed General Relativity

receives at say 5 ticks per second

1 second

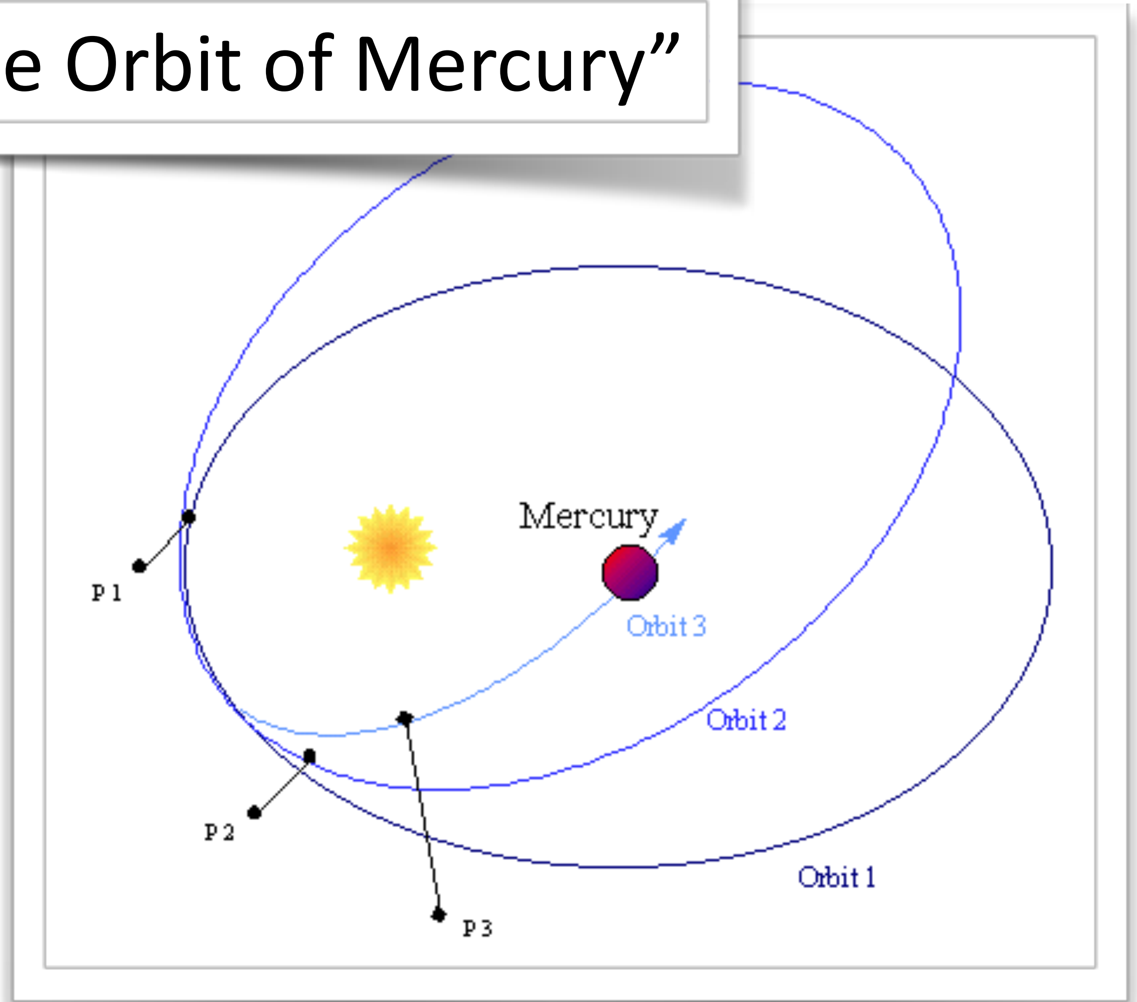
B would say that A's clock has longer between ticks:

Runs Slower

sends at say 10 ticks per second

1 second

“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

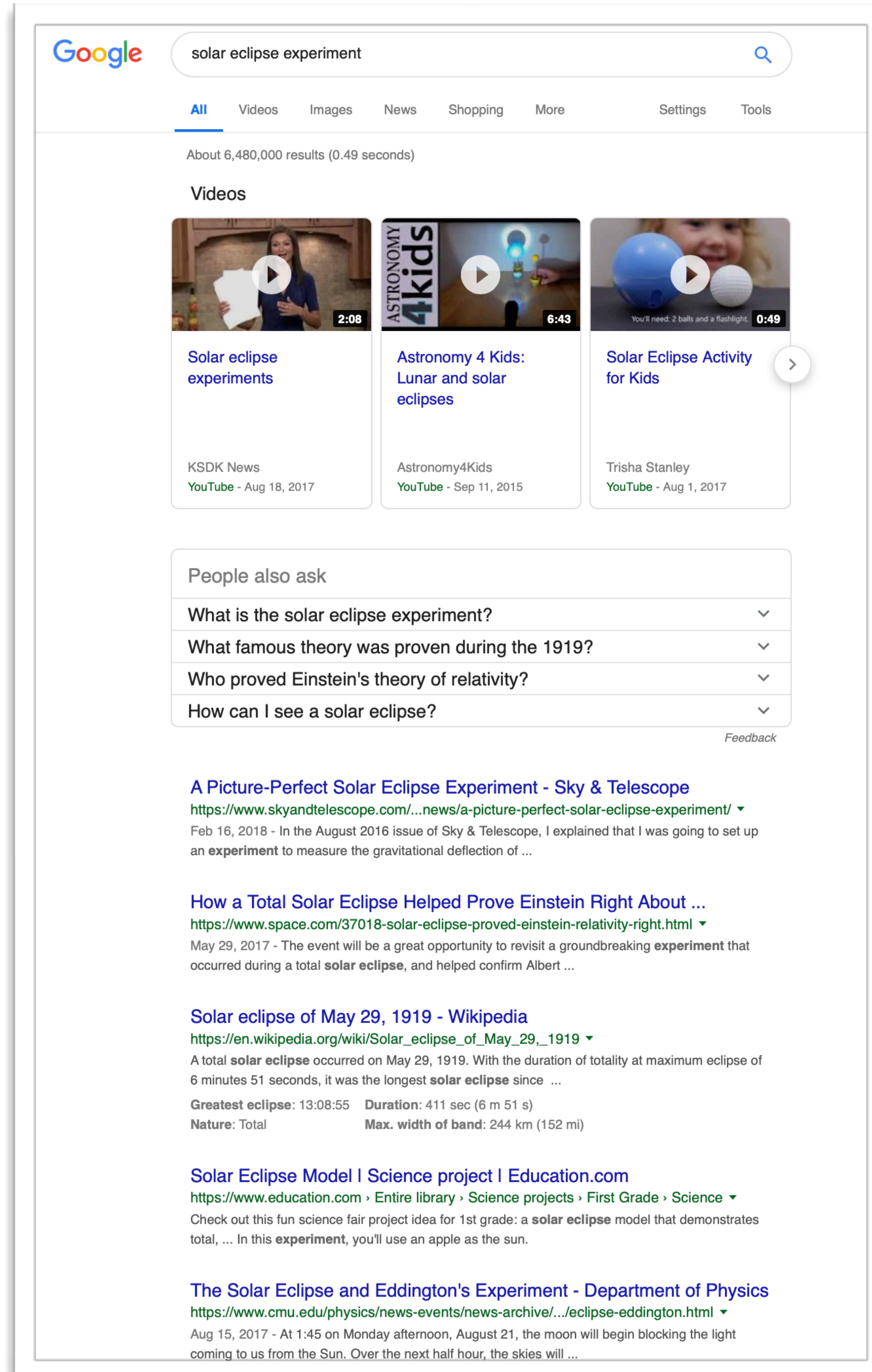
point of closest approach of the orbit advances by 43 seconds of arc per century

1916: Got precisely the right amount.

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

the mother of all experiments

the "solar eclipse" experiment



“Solar Eclipse Experiment”

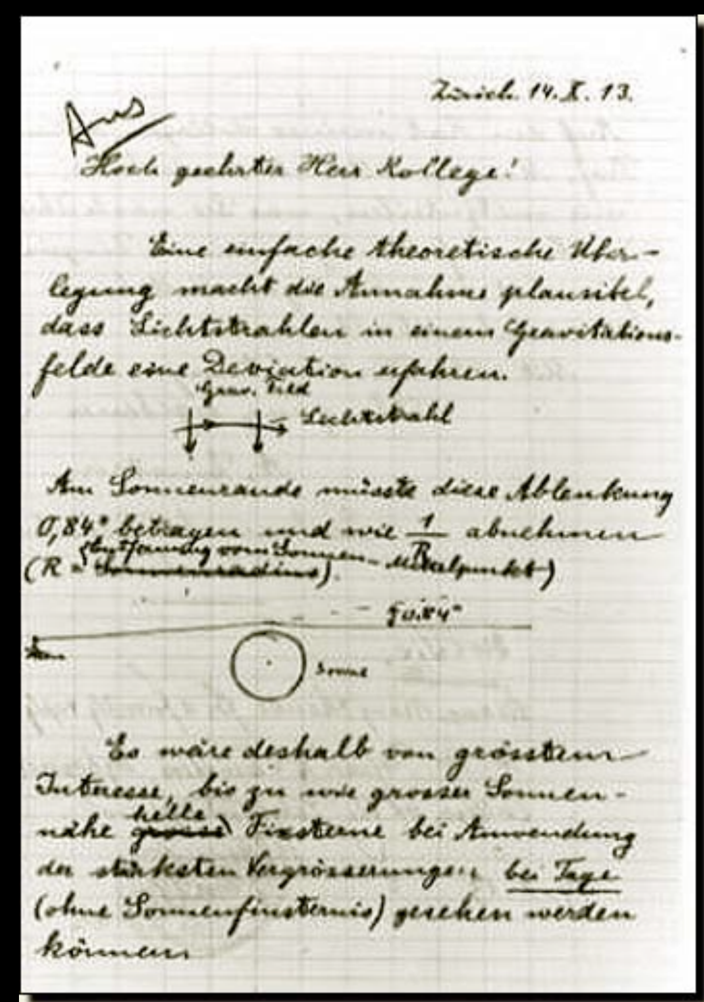
light

obeys the strong Equivalence Principle

the laser pointer…for real

The deflection should be about 1/4 milli-degree

The star is actually at A



Zürich 14.X.13.

Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

Grav. Feld

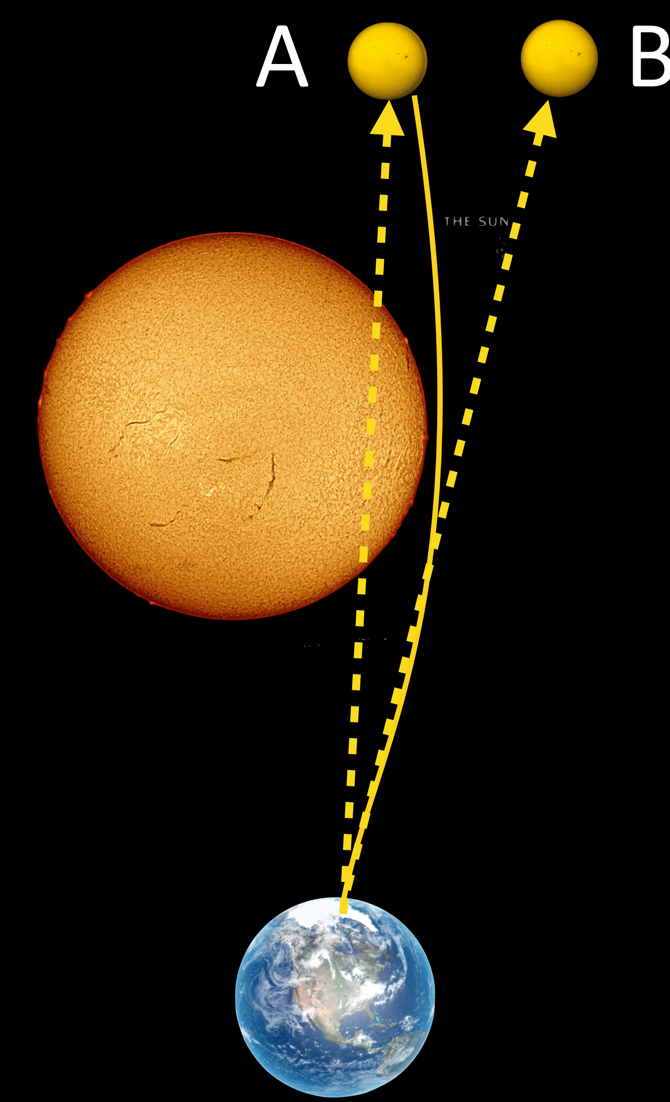
Lichtstrahl

Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie $\frac{1}{R}$ abnehmen (R = Abstand vom Sonnenmittelpunkt).

0.84"

Sonne

Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe ~~grosse~~ helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.



But it would appear to be at B

1911 calculation – initially wrong, only the $E=mc^2$ component…

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