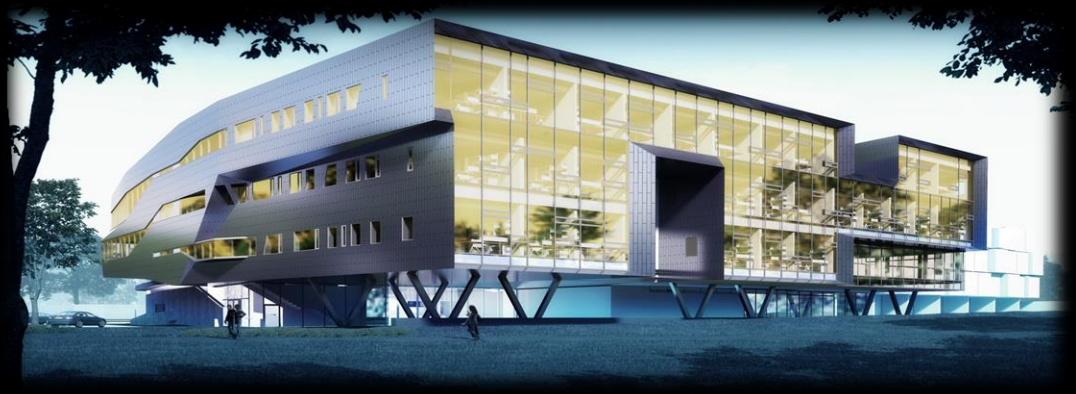
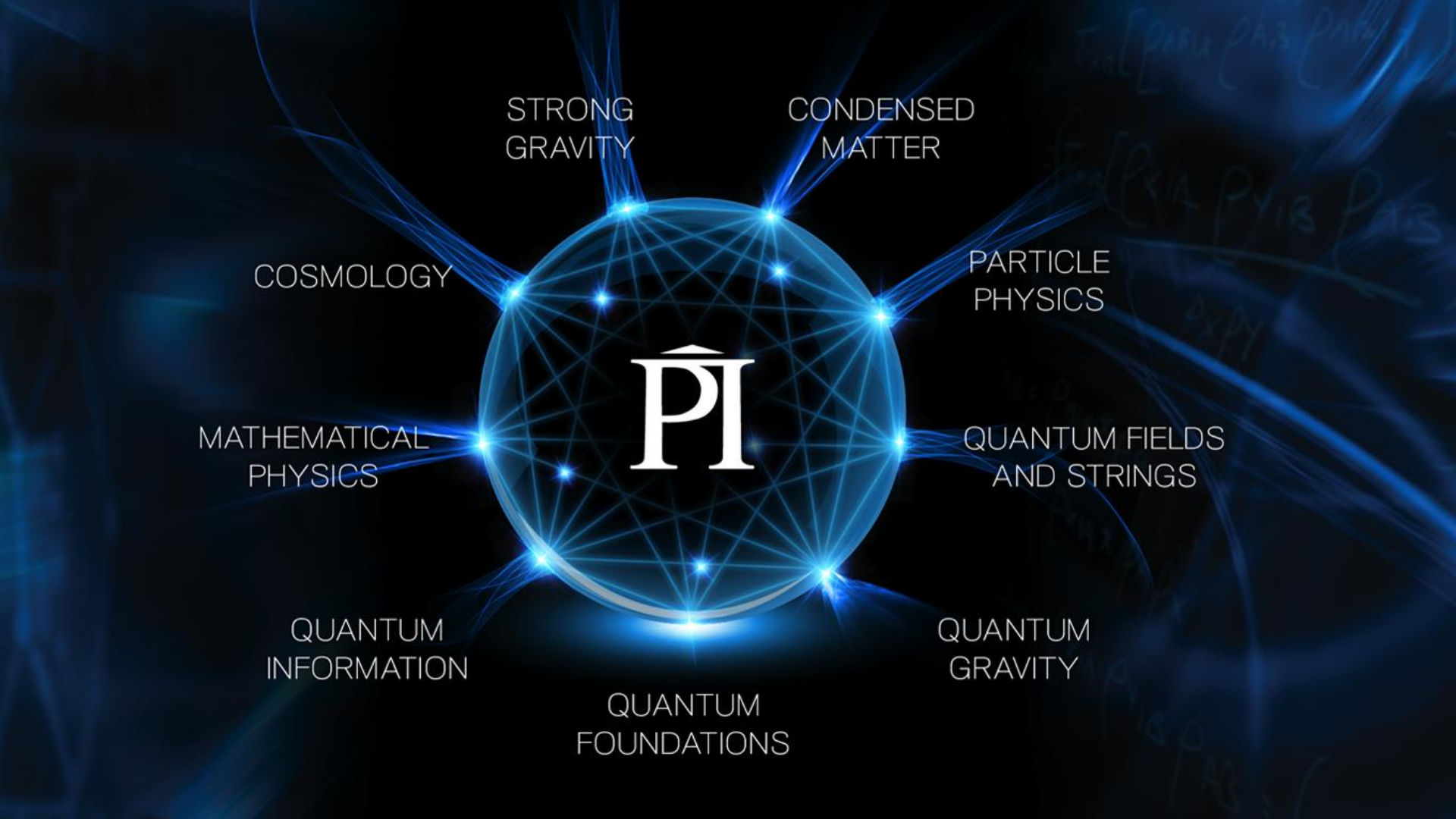
Perimeter Institute for Theoretical Physics



Curved Spacetime & GPS in the Classroom

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS


STRONG GRAVITY
CONDENSED MATTER
COSMOLOGY
PARTICLE PHYSICS
PI
MATHEMATICAL PHYSICS
QUANTUM FIELDS AND STRINGS
QUANTUM INFORMATION
QUANTUM GRAVITY
QUANTUM FOUNDATIONS

Inspirational Programs

ISSYP

Modern physics summer camp for top students from around the globe.

- Modern Physics course
- Keynote talks
- Mentor groups
- SNOLAB and IQC visits
- Social Interaction


KARI
Geometry
Reese's Pieces
HERSHEY'S
MIND
SPACE
HUGE
Mentoring
Einstein Cake Pops
TOO MUCH
Food
"Superb!"
The sun goes down
the stars come out...
My universe will never
be the same! I'm
glad you
came!
"I Feel Power"
No Force of Gravity?
TEXTIN
"I want a b
DUUUUUDE
Minkow
Geometry
But how is your Social Life?
Yay!
"Quantum black holes are black holes."
E=mc
Energy is mass.
Running
Hi Im
PI
POKER
AI
IQ

Inspirational Programs

Einstein Plus

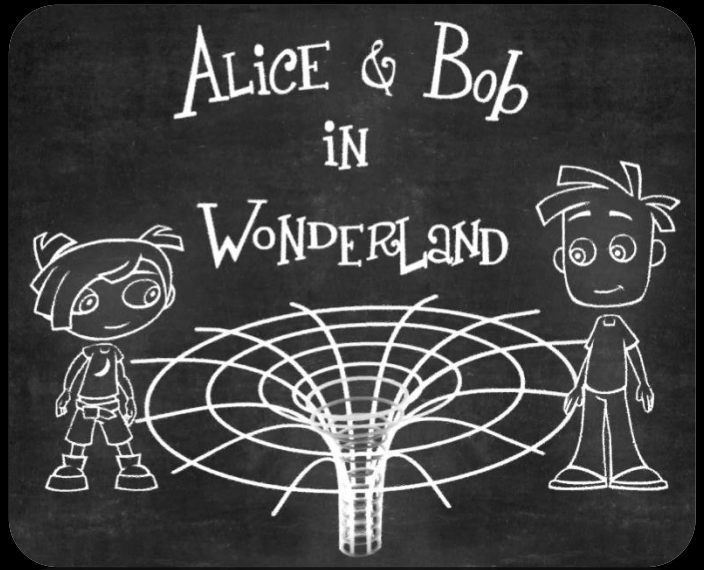
Physics summer camp for high school teachers from around the globe.

- Physics workshops and discussions
- Keynote talks, researcher interaction
- IQC tour
- Social Interaction

Classroom Resources

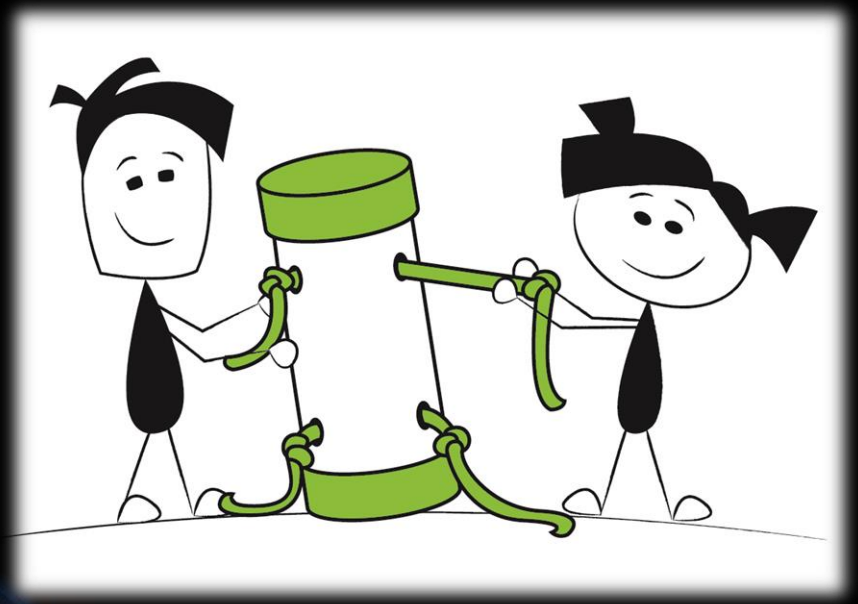
Teacher-Researcher Collaboration

Professional Production



PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

Scientific Models



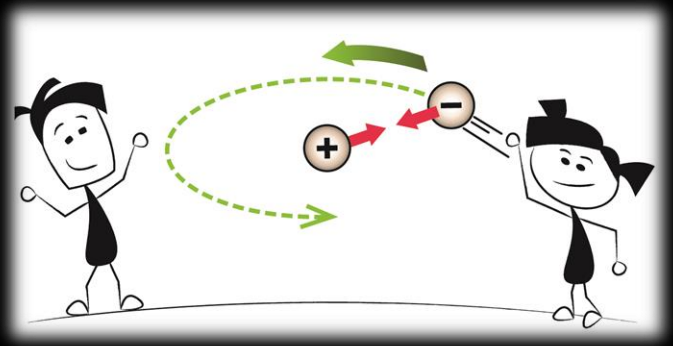
The great tragedy of Science — the **slaying of a beautiful hypothesis by an ugly fact**.

- T.H. Huxley

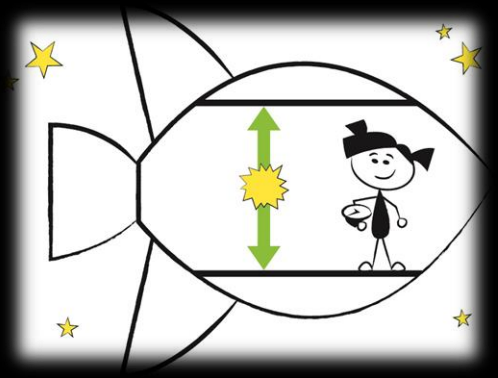
About *Revolutions in Science*

Students engage with three powerful **ideas**:

Gravity



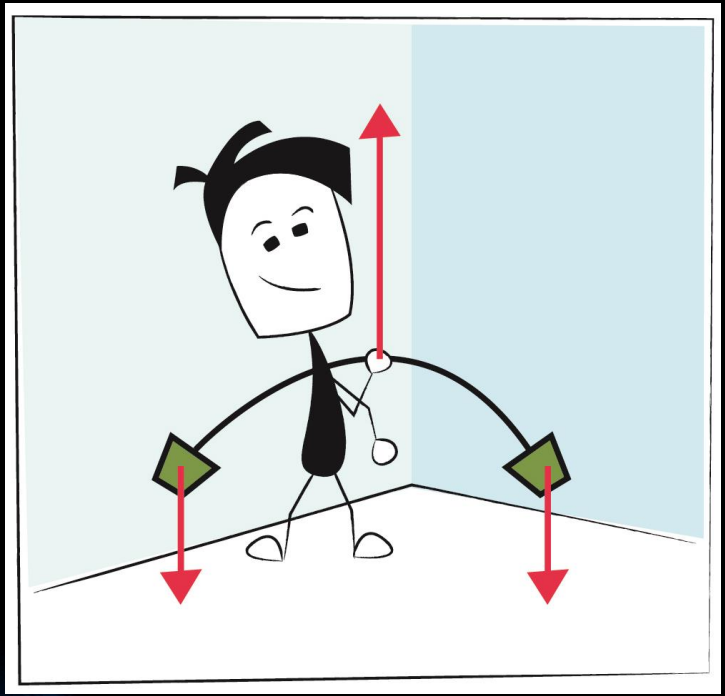
The atom



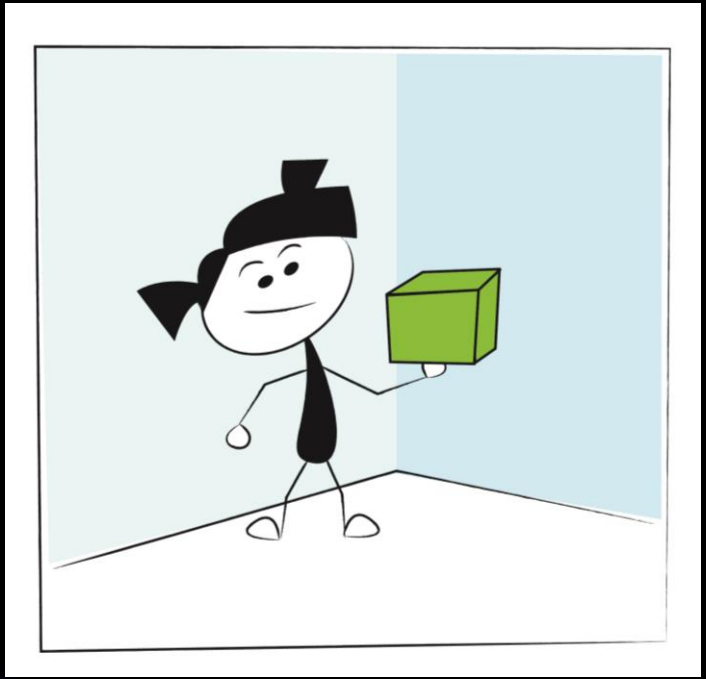
Time

Why does this rod bend?

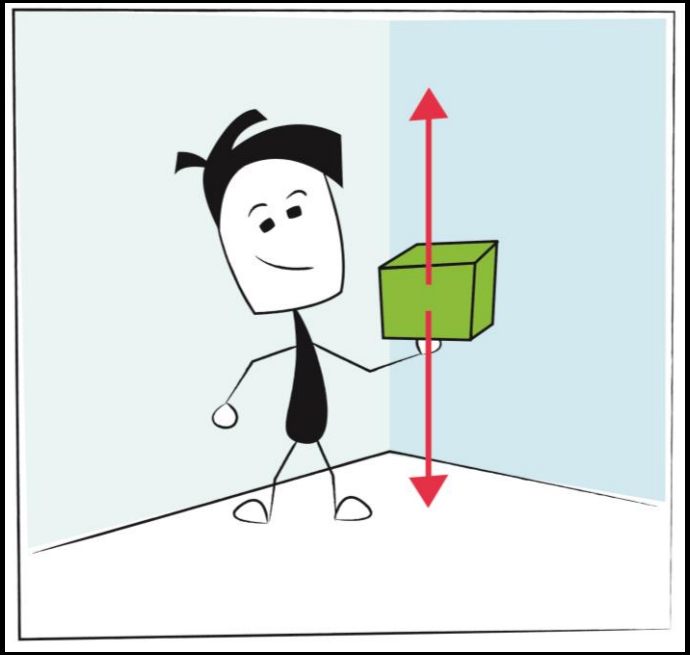
One force pulls down another pushes up



Why do objects feel heavy?

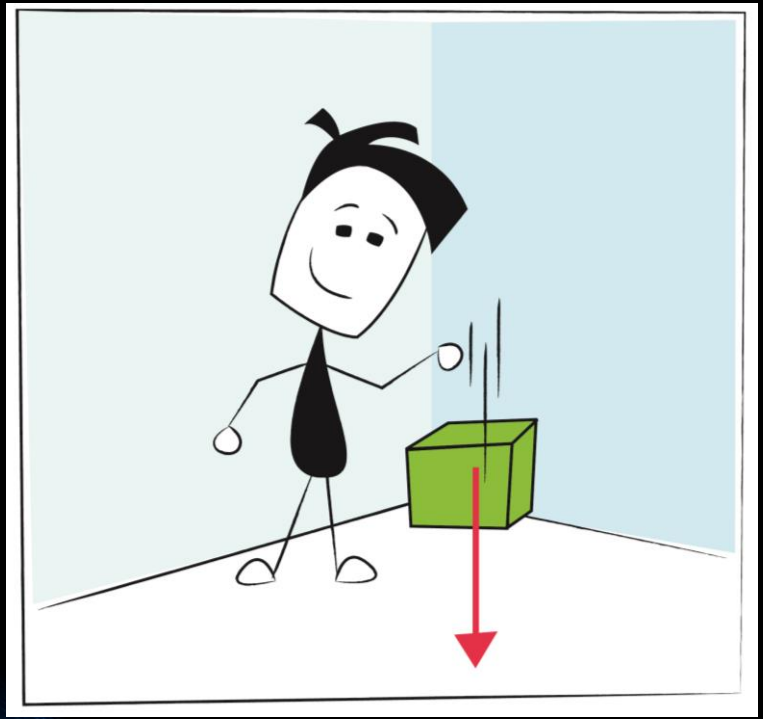


You push up to oppose the force of gravity



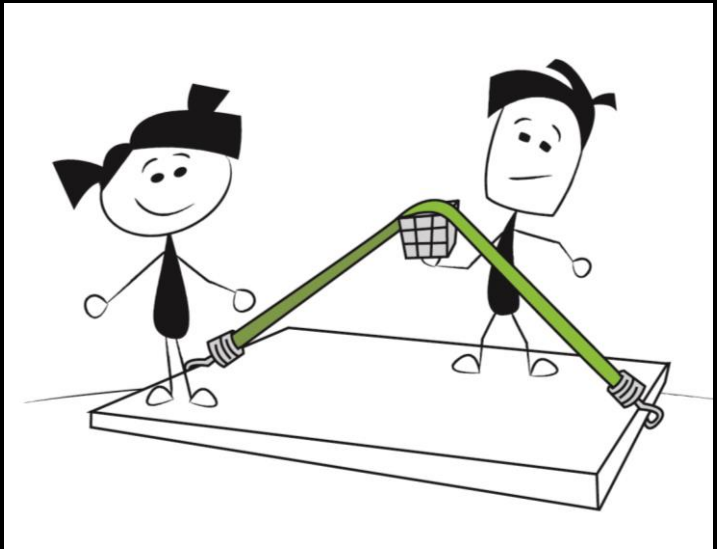
Why do objects fall?

The force of gravity pulls them down



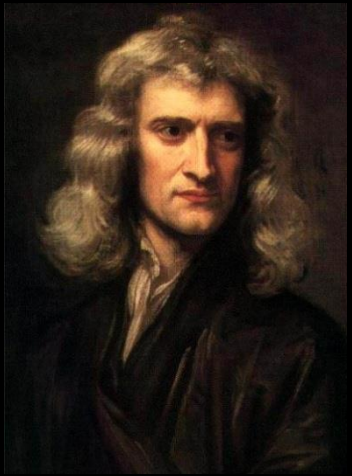
Force Model of Gravity

Gravity is like an invisible bungee cord

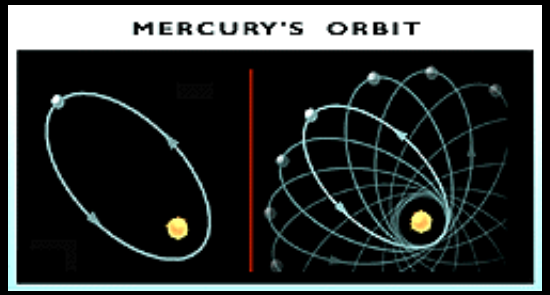


But…What is GRAVITY?

Newton: Gravity is a force

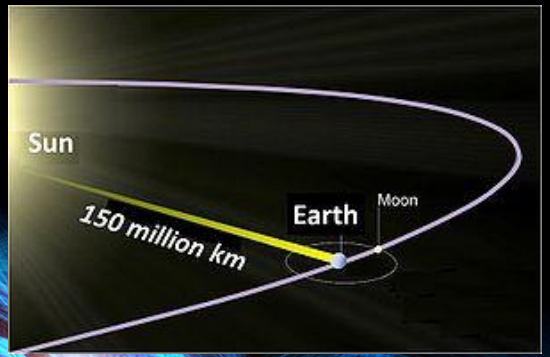


Newtonian gravity works…right?



Experiment (1859)

Force model predicts the wrong orbits



Theory (1905)

Force model violates speed of light limit

"That gravity should be inate, inherent, and essential to matter so that one body may act upon another, at a distance through vacuum, without the mediation of anything else…is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking, can ever fall into it."

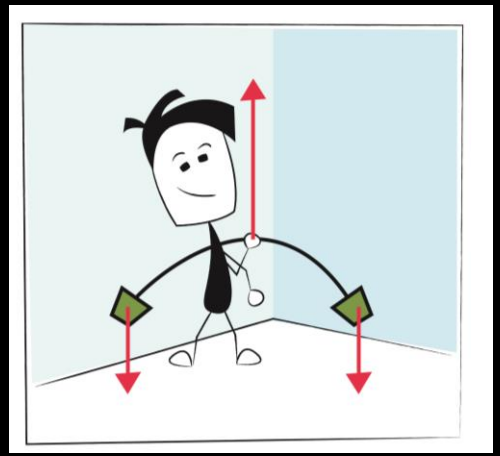
- Isaac Newton

so....

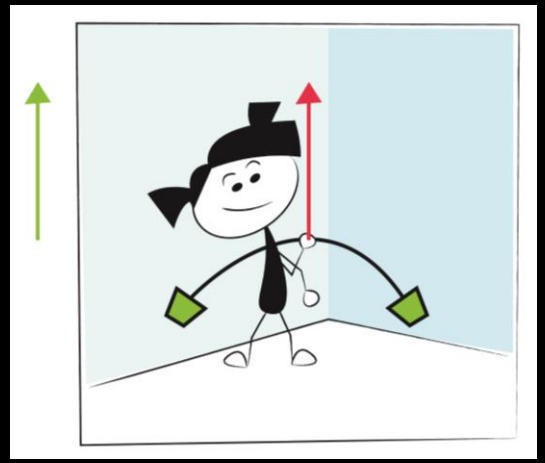
something is *wrong* with our force model for GRAVITY

Student Worksheet

Comparing two models of gravity



Force Model

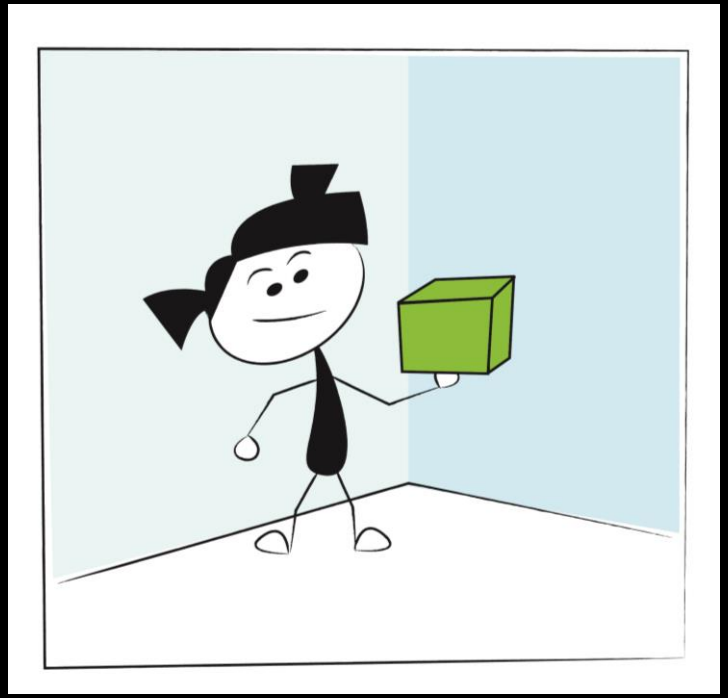


Acceleration Model

How else can I make this rod bend?

Explaining WEIGHT

How can I create "weight" using acceleration?



Explaining FREE FALL

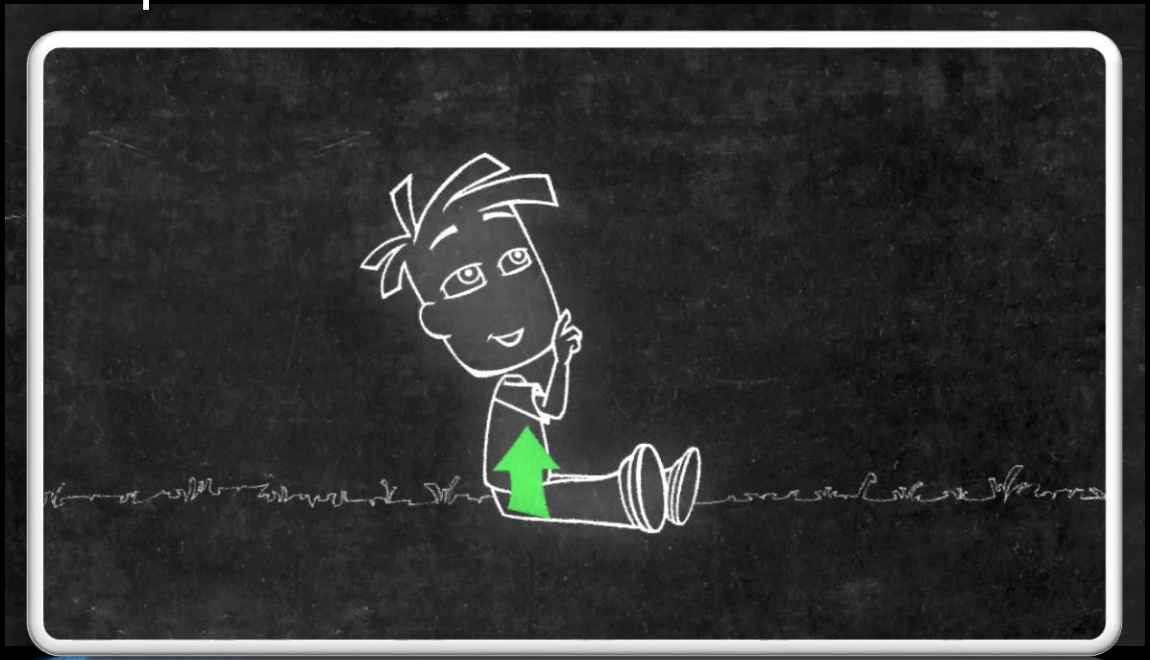
How can I cause free fall motion using acceleration?

Acceleration Model

Gravity is an inference - not a real force

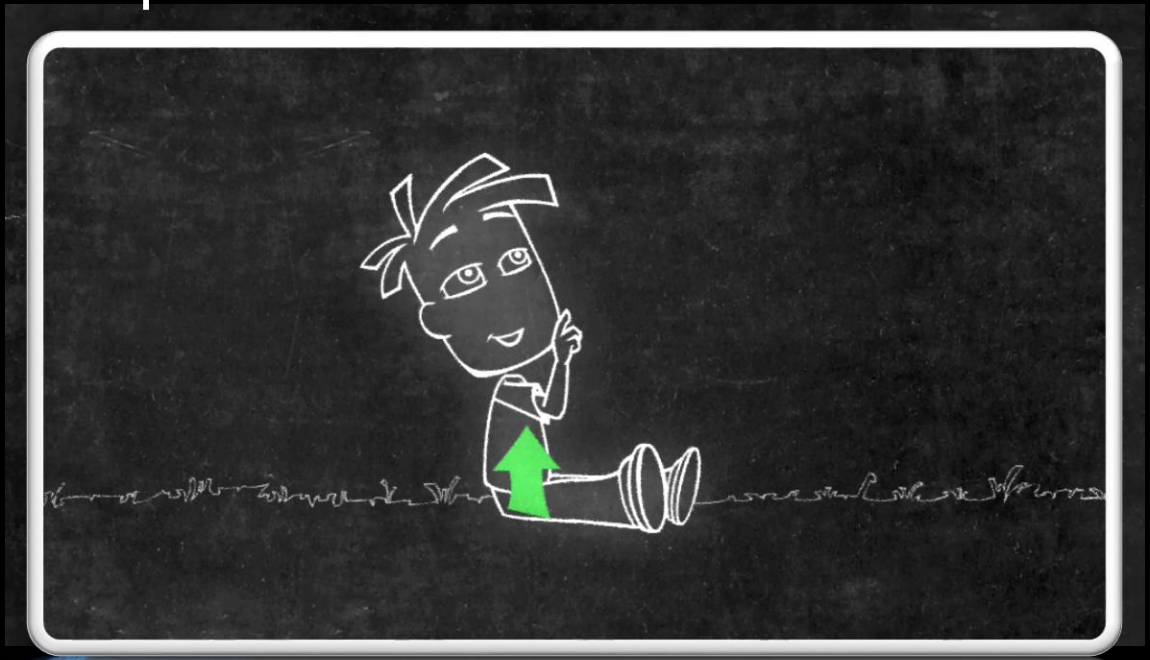
Animation

What keeps us stuck to the Earth?



Animation

What keeps us stuck to the Earth?



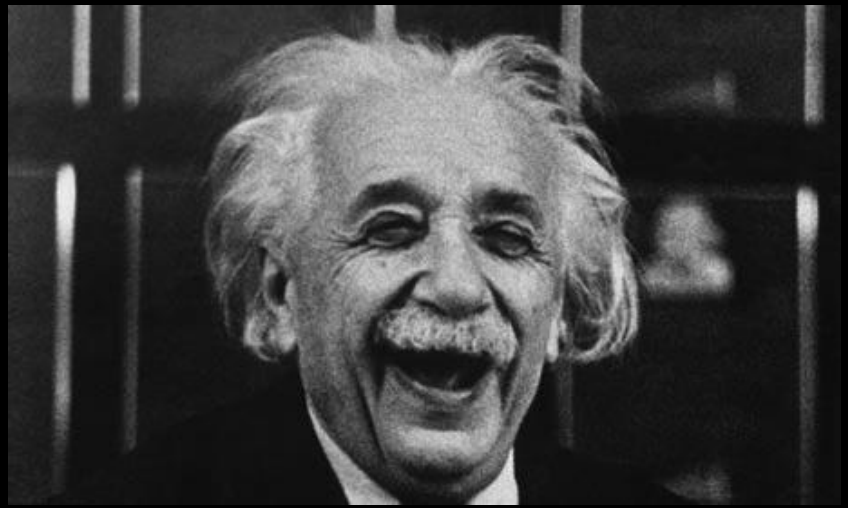
The Big Question

How can the ground be *accelerating* up without *moving* up?

Acceleration Model of Gravity

Acceleration in one direction is identical to a force in the other direction!

-Einstein's "happiest thought"

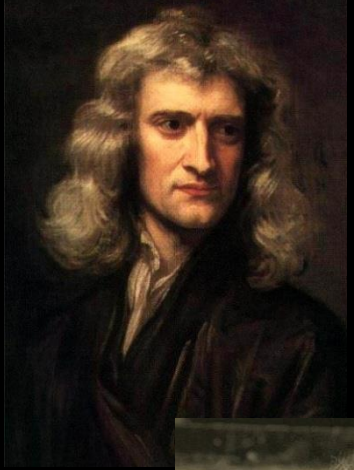


Gravity isn't a force pulling us down.

We are accelerating up!

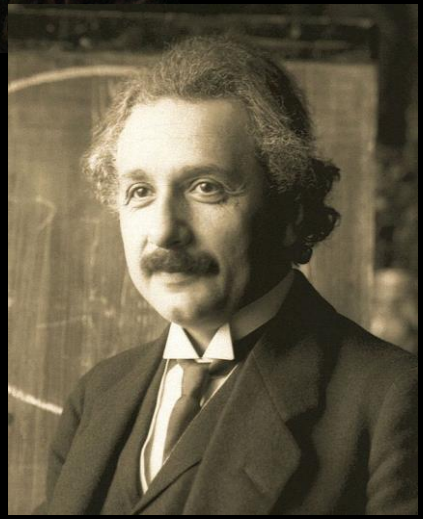
Newton: Gravity is a force

FEELS RIGHT, but doesn't survive experimental tests

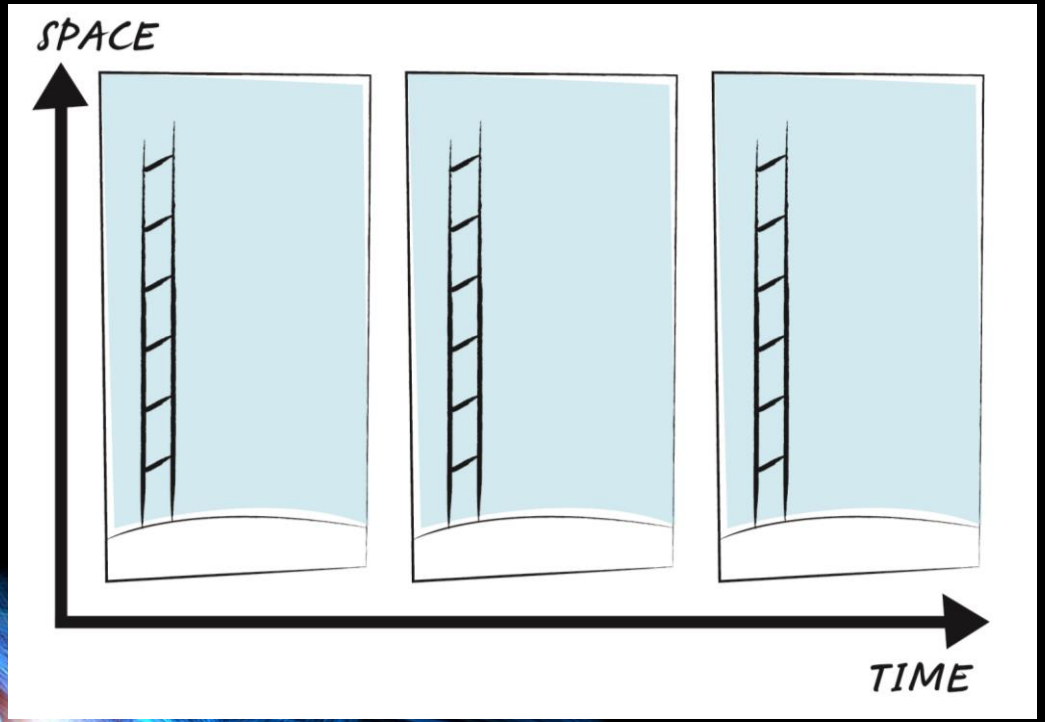


Einstein: Acceleration Model

FEELS WEIRD but could work...
... But earth isn't expanding!

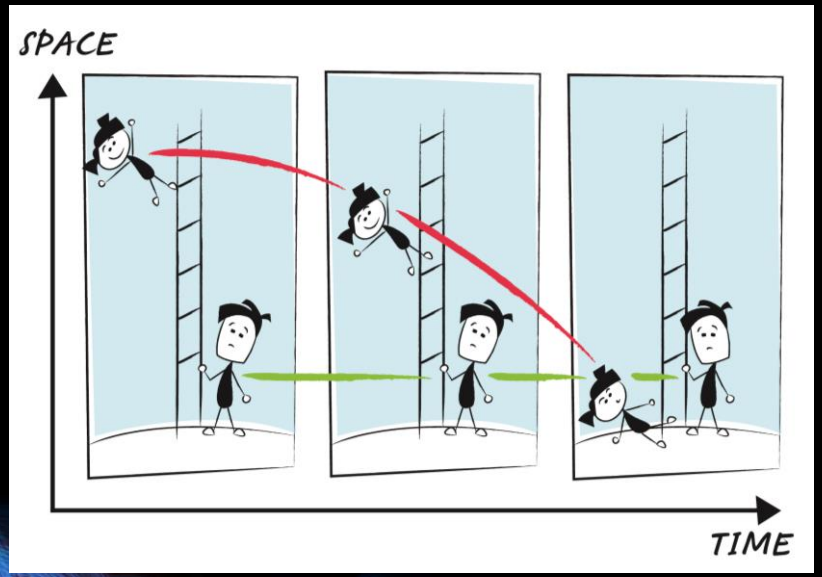


Spacetime diagram



Curved lines on spacetime diagram mean the object accelerated.

Spacetime diagram

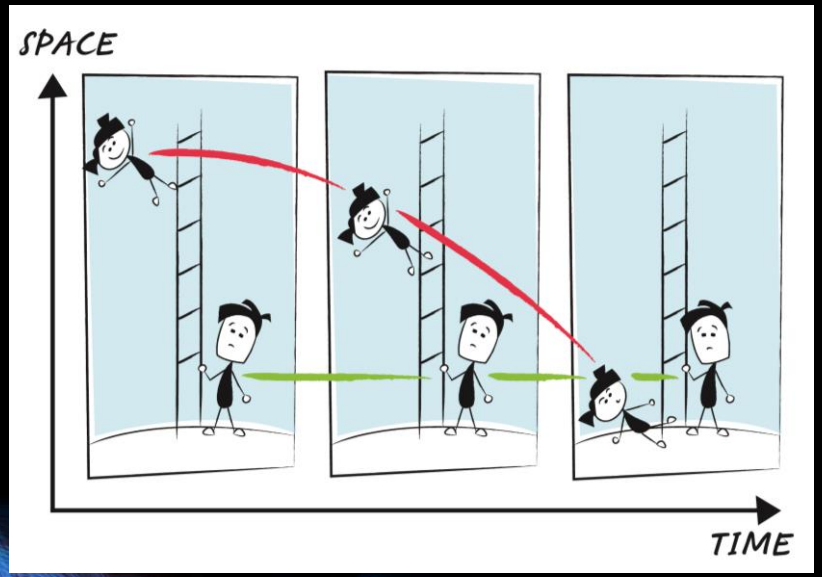


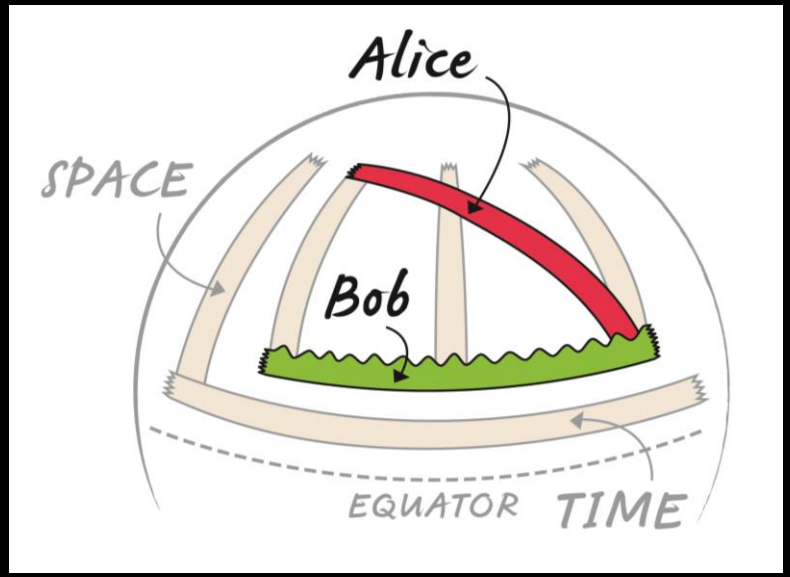
Curved lines on spacetime diagram mean the object accelerated.

No good!
Wanted Alice's path to be straight and Bob's curved.

How can we draw this graph so that Alice is a straight line.
And Bob is a curved line that is parallel to the time axis?

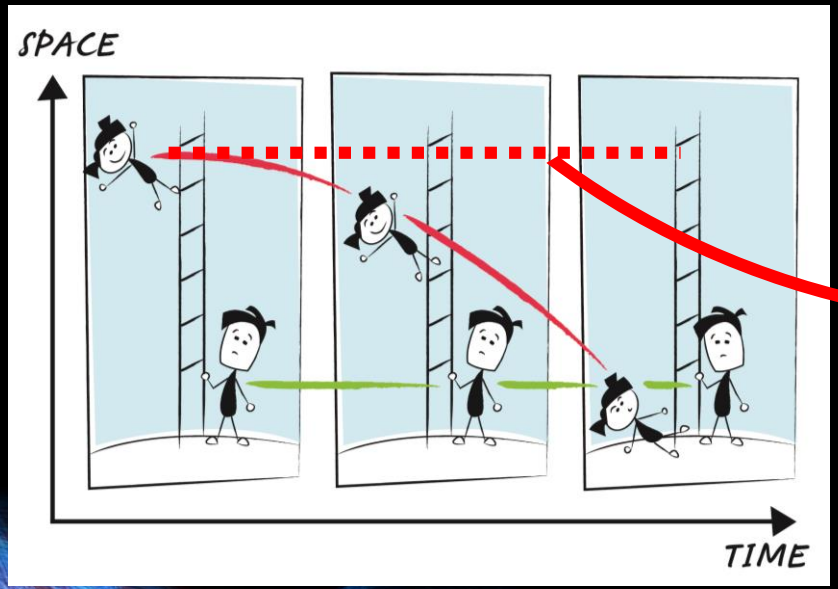
Curved Spacetime

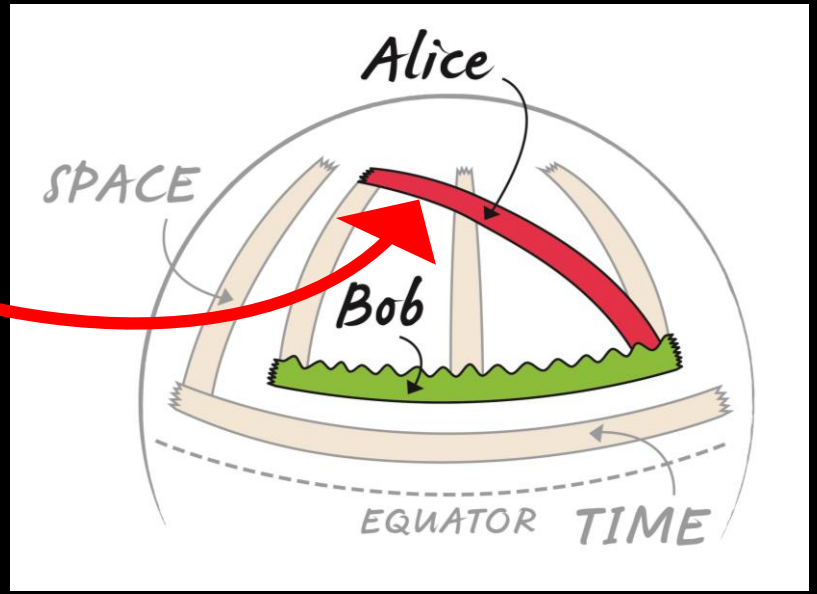




Alice's path *stays straight* (no force, no acceleration)

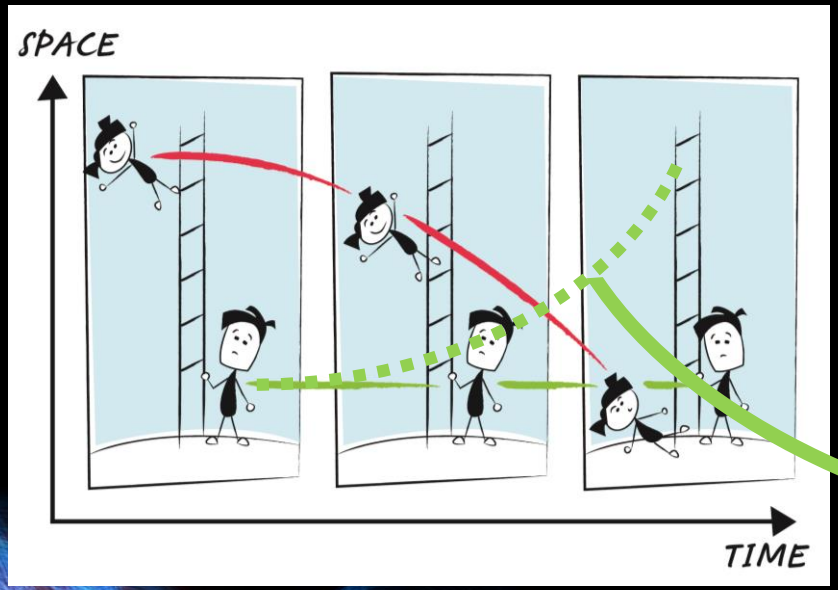
…and yet she is *falling* from the top of the ladder to the bottom!

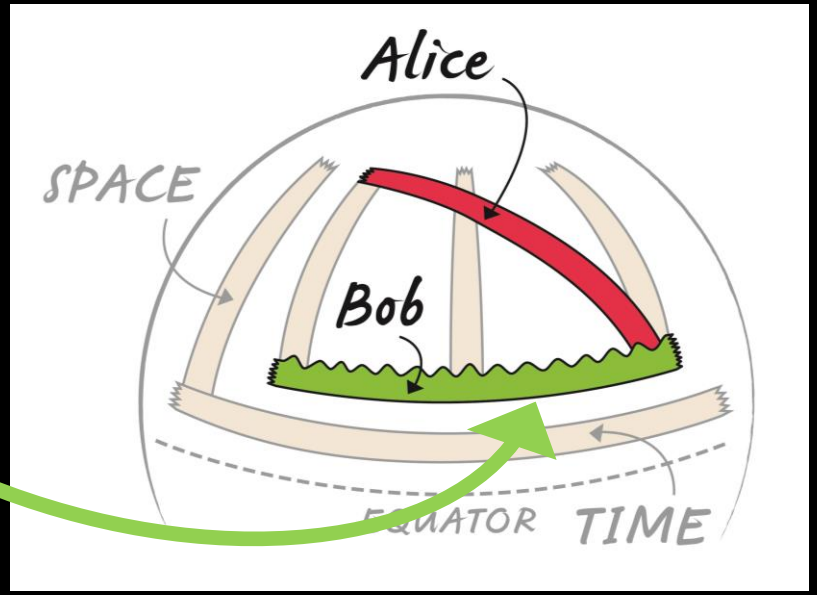




Bob's path *curves up* (he feels upward force and acceleration)

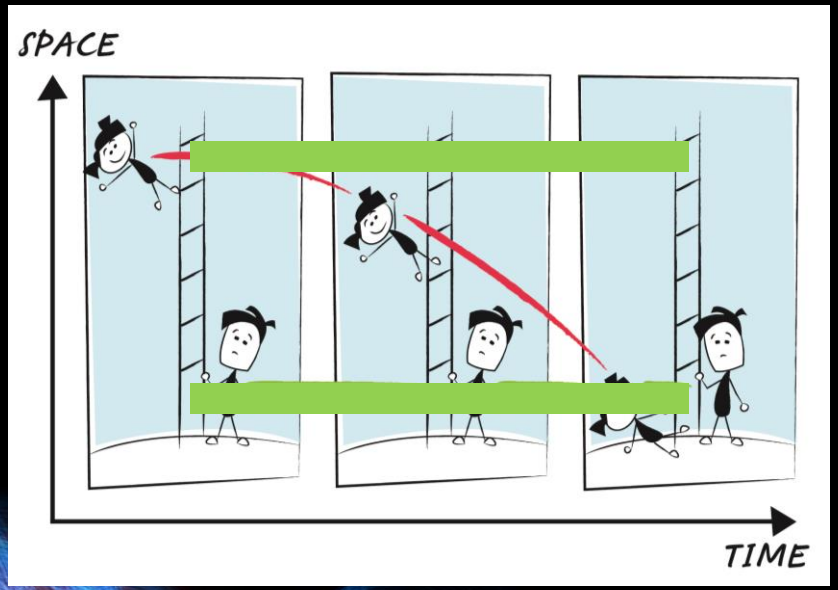
…and yet he is not *moving* up!

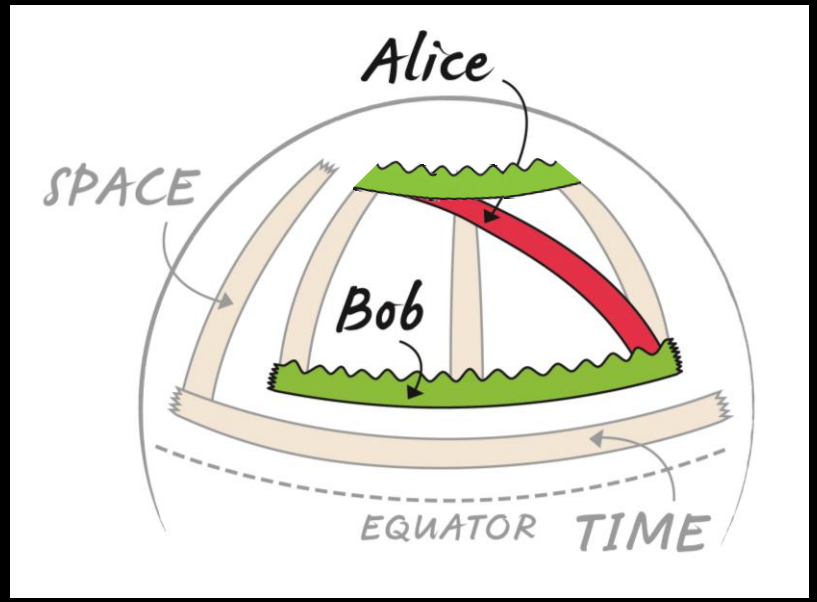




Models cannot be proven *right*, only *wrong*

Curved spacetime predicts time dilation





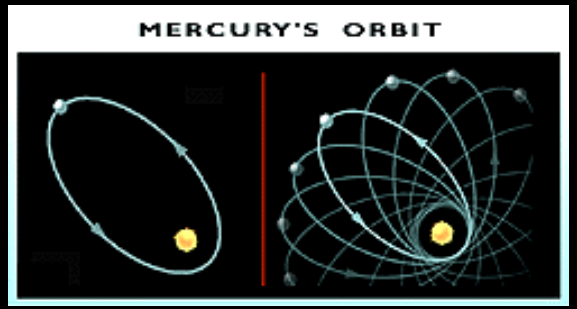
GPS confirms that time dilation is ***REAL!***

Time dilation proves the force model is *WRONG*

GPS confirms that time dilation is ***REAL!***

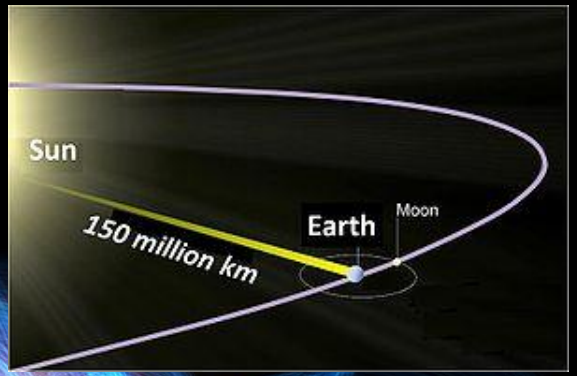
Time dilation proves the force model is *WRONG*

Curved spacetime also solves other issues…



Experiment (1915)

Predicts the *correct* orbits



Theory

Does *not* violate speed of light limit

Summary:

Two competing models

Force model *fails*. Acceleration model *succeeds*.

Curved spacetime was the revolutionary idea.

So what is gravity?

Gravity is the curvature (a.k.a. warping) of spacetime.

The Earth does not exert a force on objects...it curves spacetime so that the ground is *accelerating* up without *moving* up.

We experience this acceleration through weight, freefall, etc.

So what is gravity?

MASS tells SPACETIME how to CURVE

CURVED SPACETIME tells MATTER how to MOVE

Take-away messages:

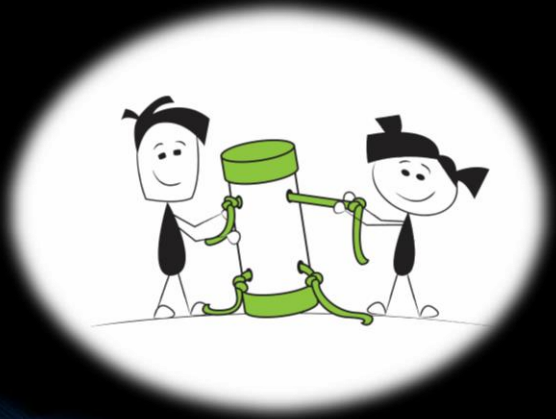
Creating and revising models…

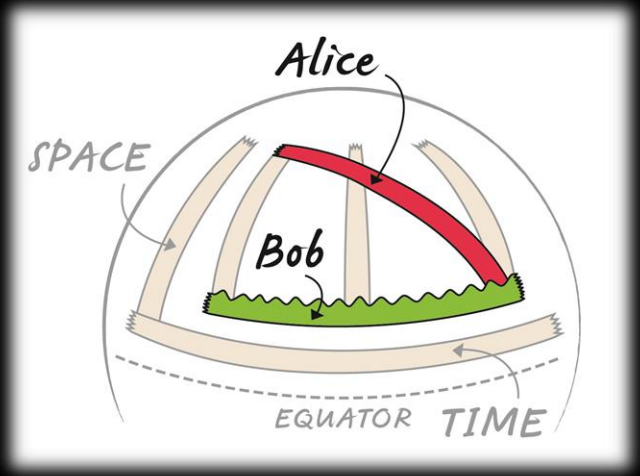
…requires creative & critical thinking.

What feels right/wrong is *irrelevant*…

…experiment is the judge.

Science is a powerful way of thinking.





Thank You!!

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