The Force That Isn't a Force

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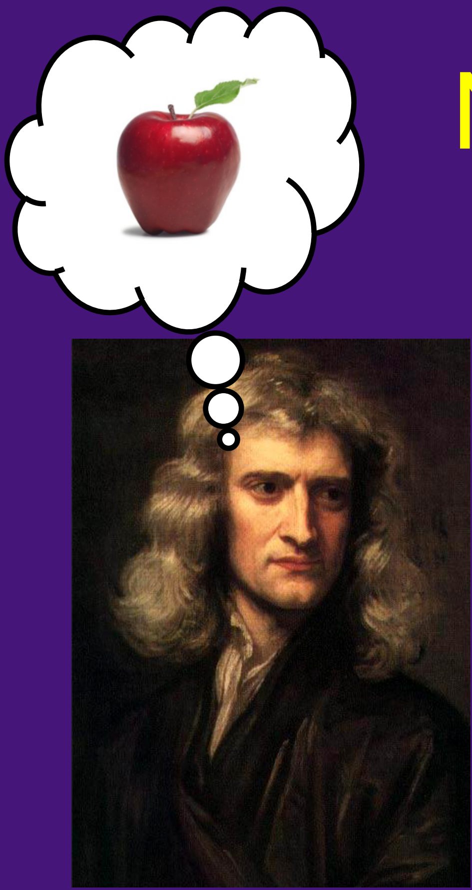
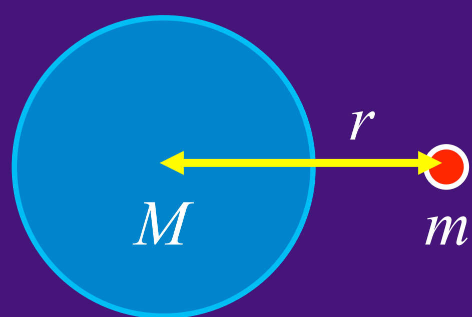
The old revolution



Newton's revolution

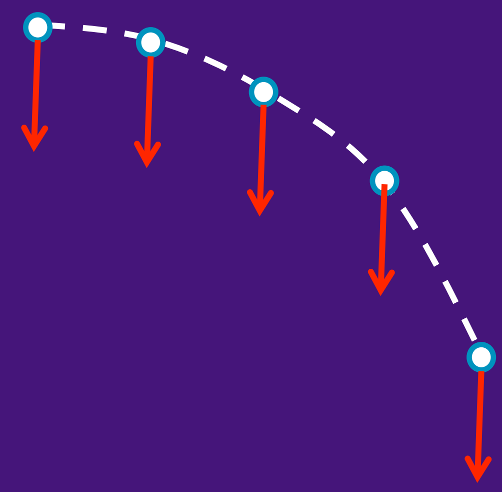
What is gravity?

- Gravity is a weak, long-range, attractive force between masses.
- Gravity is universal -- it acts between every pair of masses everywhere.
- Force F between masses M and m separated by distance r :



$$F = \frac{GMm}{r^2}$$

Projectiles and satellites



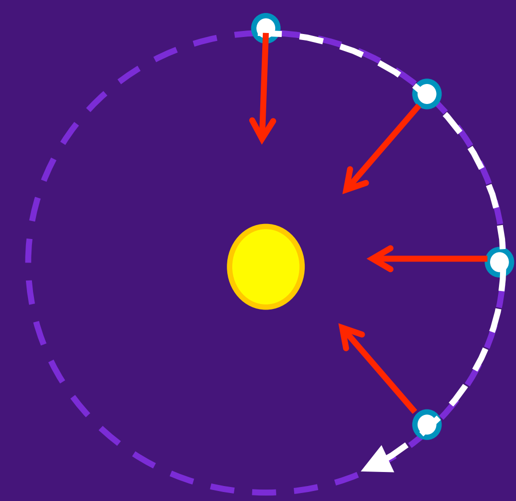
Projectile motion

- horizontal: constant speed
- vertical: accelerate downward

Orbital motion

- Acceleration toward a central body
- Simplest situation: circular orbit

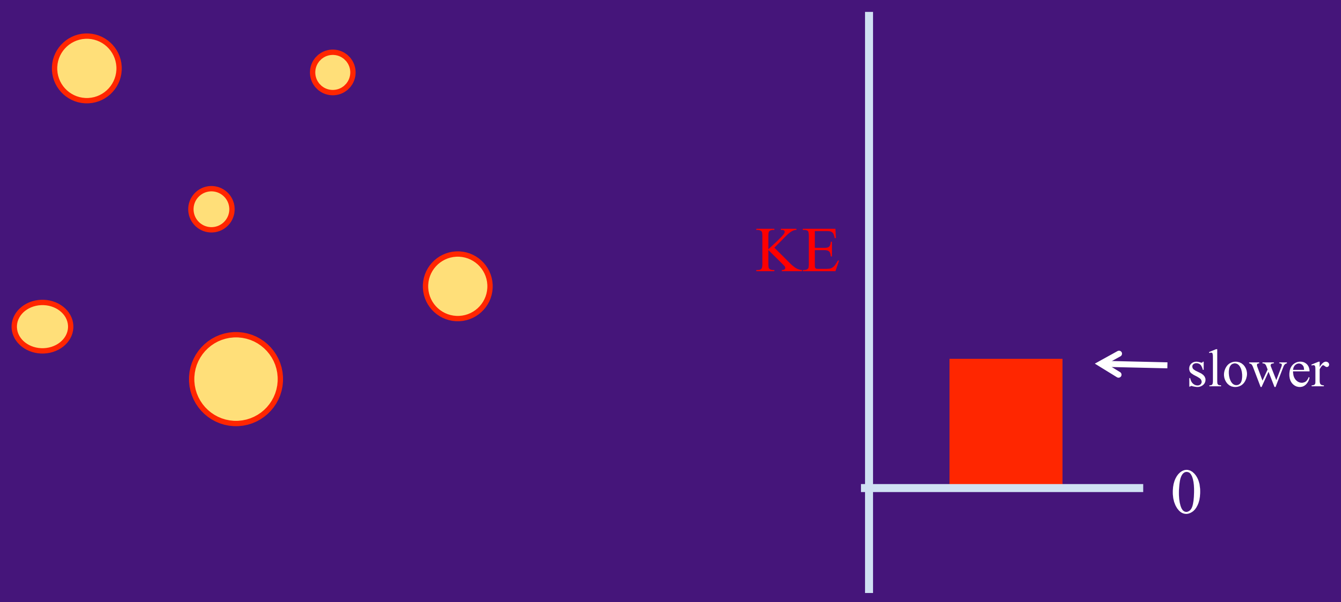
$$v_{circ} = \sqrt{\frac{GMm}{r}}$$



Energy and motion

Kinetic energy (KE) is energy due to motion.

- KE = 0 when everything is at rest
- Faster motion means higher KE.



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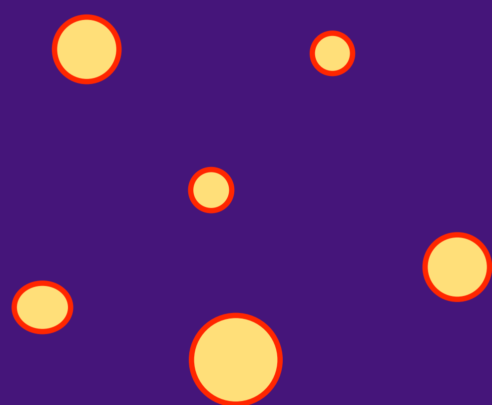
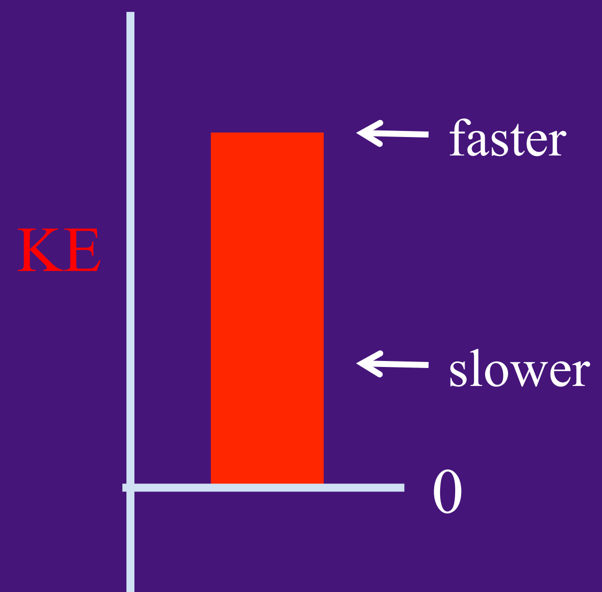
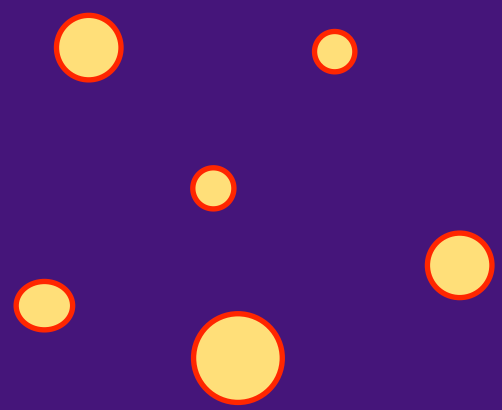


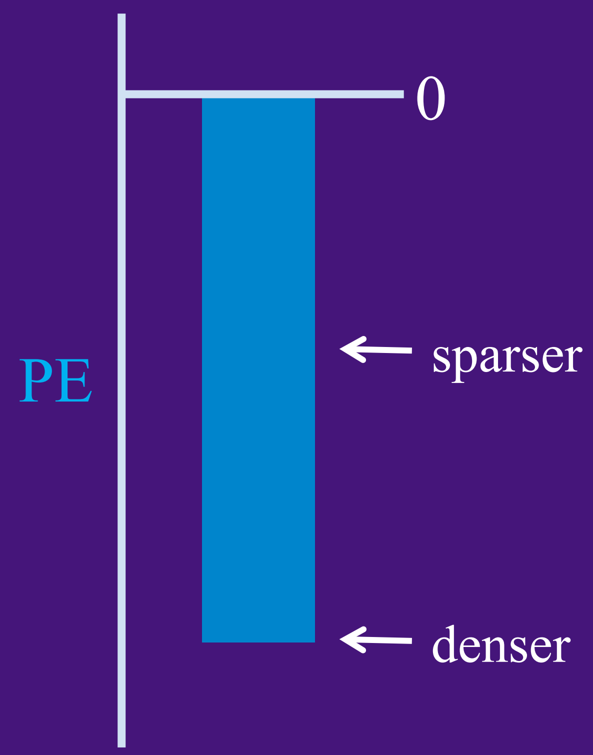


Gravitational potential energy

Potential energy (PE) is "stored" energy due to a force

- Gravitational PE = 0 when masses are very far apart.
- PE is negative -- more negative when masses are closer together

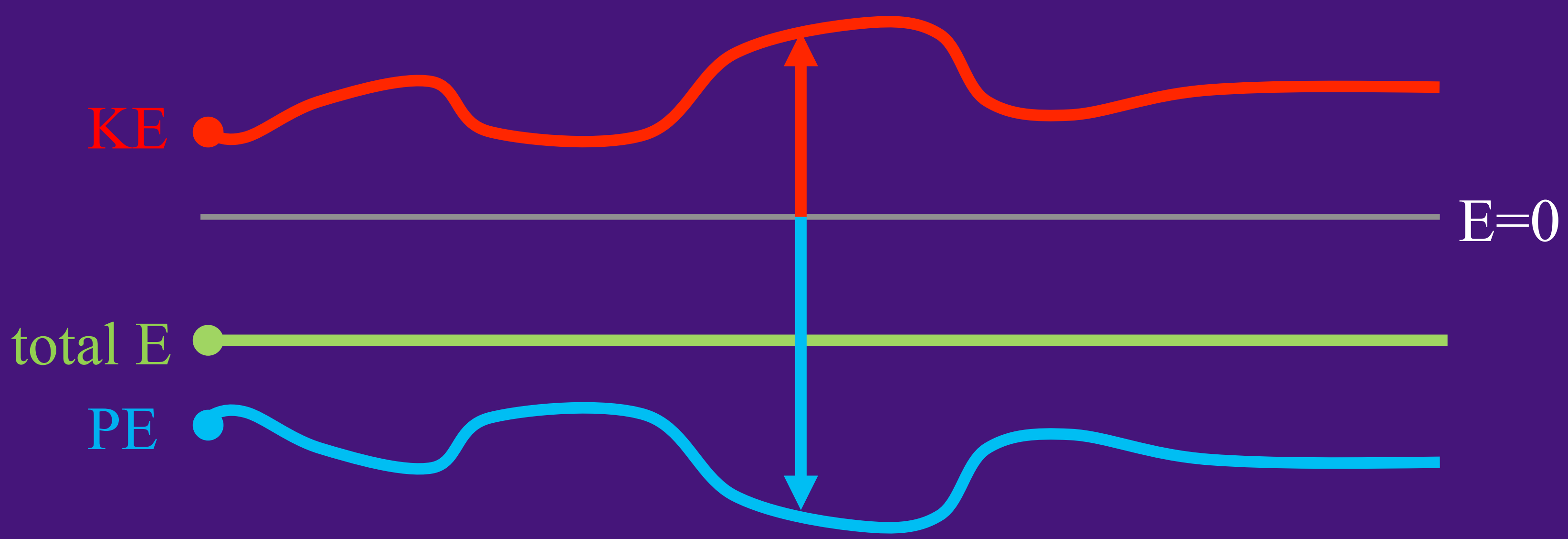




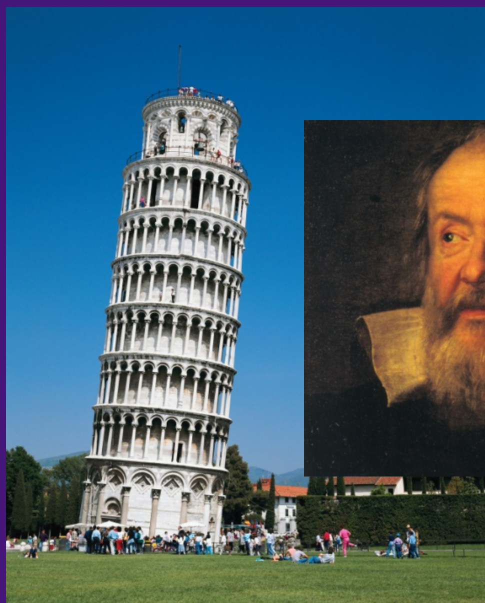
Conservation of energy

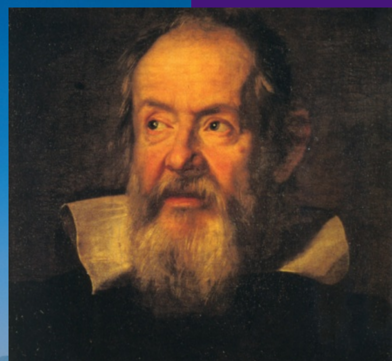
Other types of energy: heat, chemical, electrical, ...

- Only gravitational forces: KE + PE = E (const.)
- In general, total energy is conserved.



Equivalence





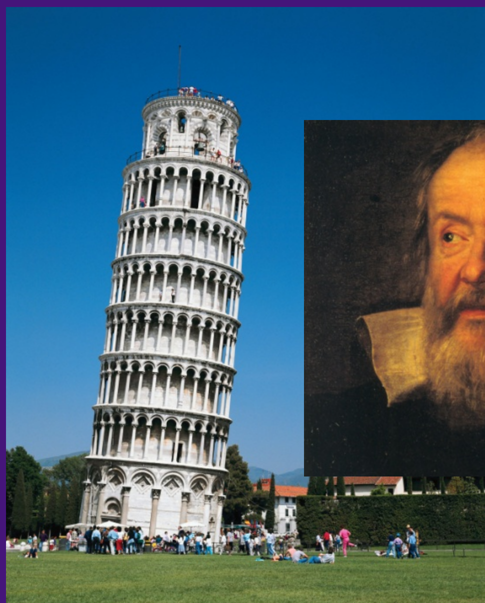
Galileo: Everything falls freely with the same acceleration

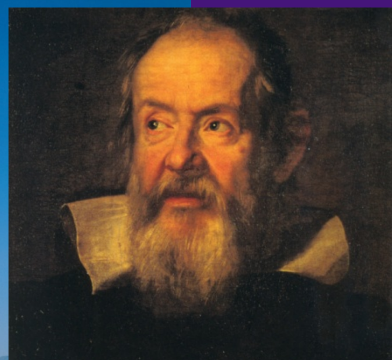
This is independent of mass and composition. (Small effects due to air resistance.)

Newtonian explanation: Inertial mass = gravitational mass

$$\cancel{m}a = \frac{GM\cancel{m}}{r^2}$$

Equivalence





Galileo: Everything falls freely with the same acceleration

This is independent of mass and composition. (Small effects due to air resistance.)

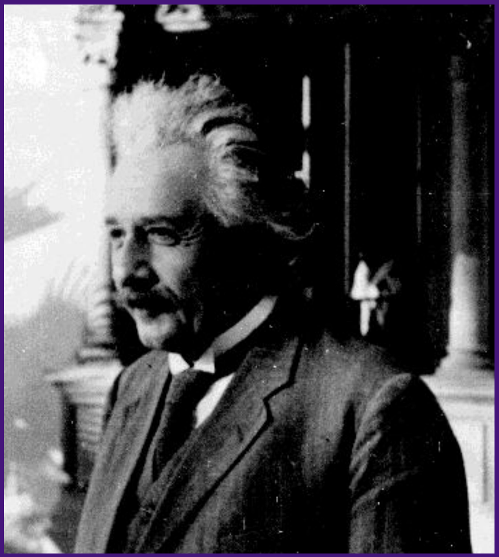
Newtonian explanation: Inertial mass = gravitational mass

$$a = \frac{GM}{r^2}$$

Exactly the same for any object at a given distance from the Earth

The new revolution

Einstein's revolution



What is gravity?

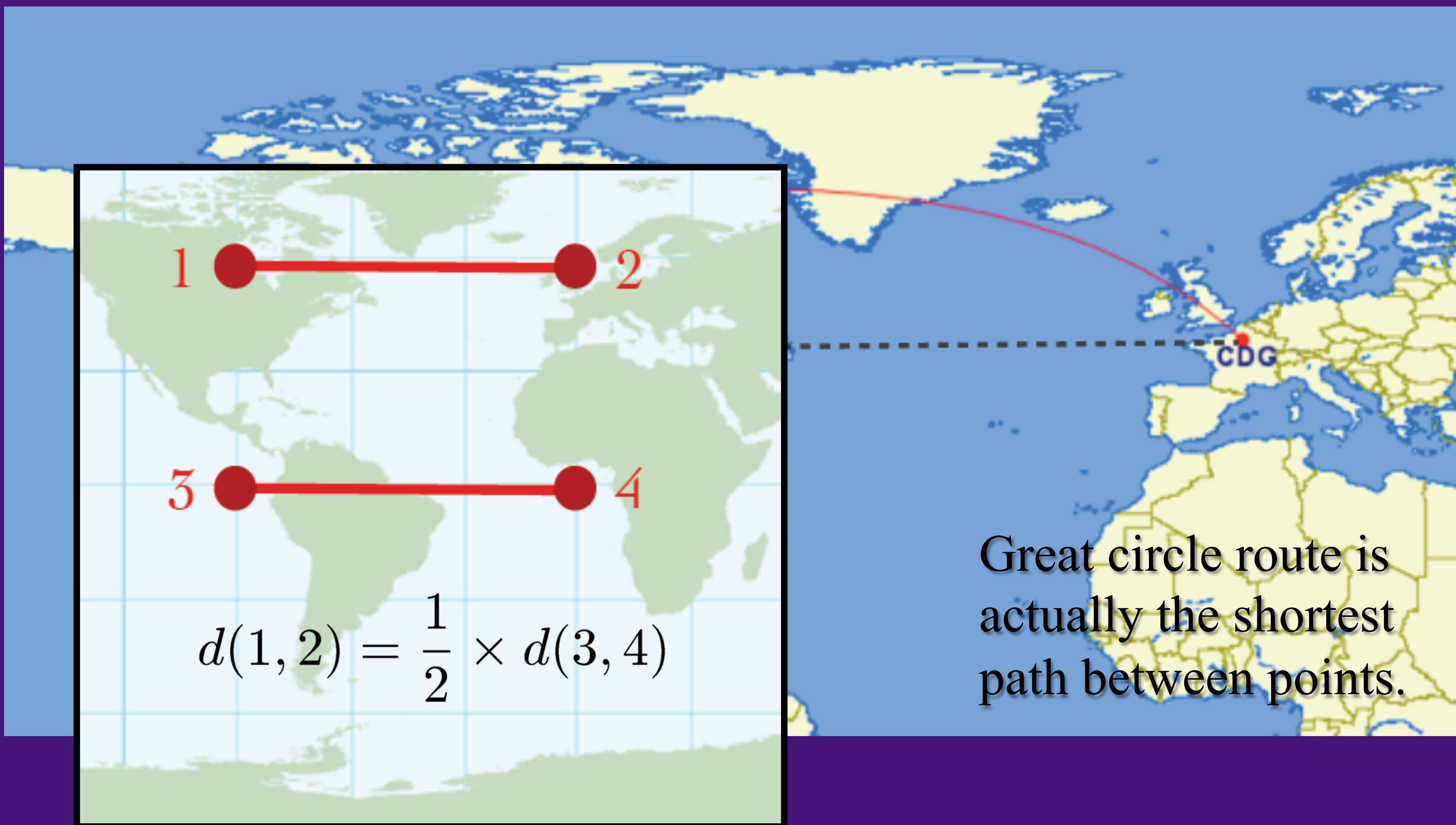
- Principle of equivalence is the key -- gravity affects all phenomena alike!
- Gravity is not really a force. It is really curvature of spacetime!
- Apparently curved paths of freely-falling bodies are really "straight" geodesics

What is a straight line?

Ordinary geometry:

A straight line is the path of shortest length between two points.

Geodesic paths



$$d(1,2) = \frac{1}{2} \times d(3,4)$$

Great circle route is actually the shortest path between points.

What is a straight line?

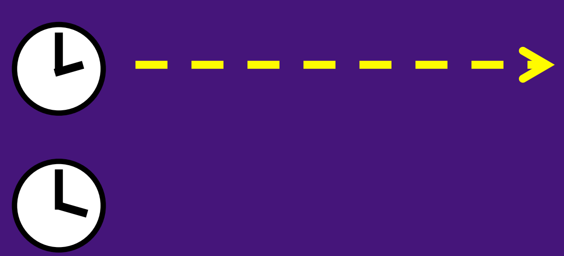
Ordinary geometry:

A straight line is the path of shortest length between two points.

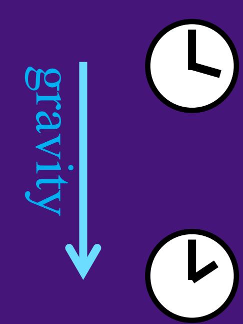
Spacetime geometry:

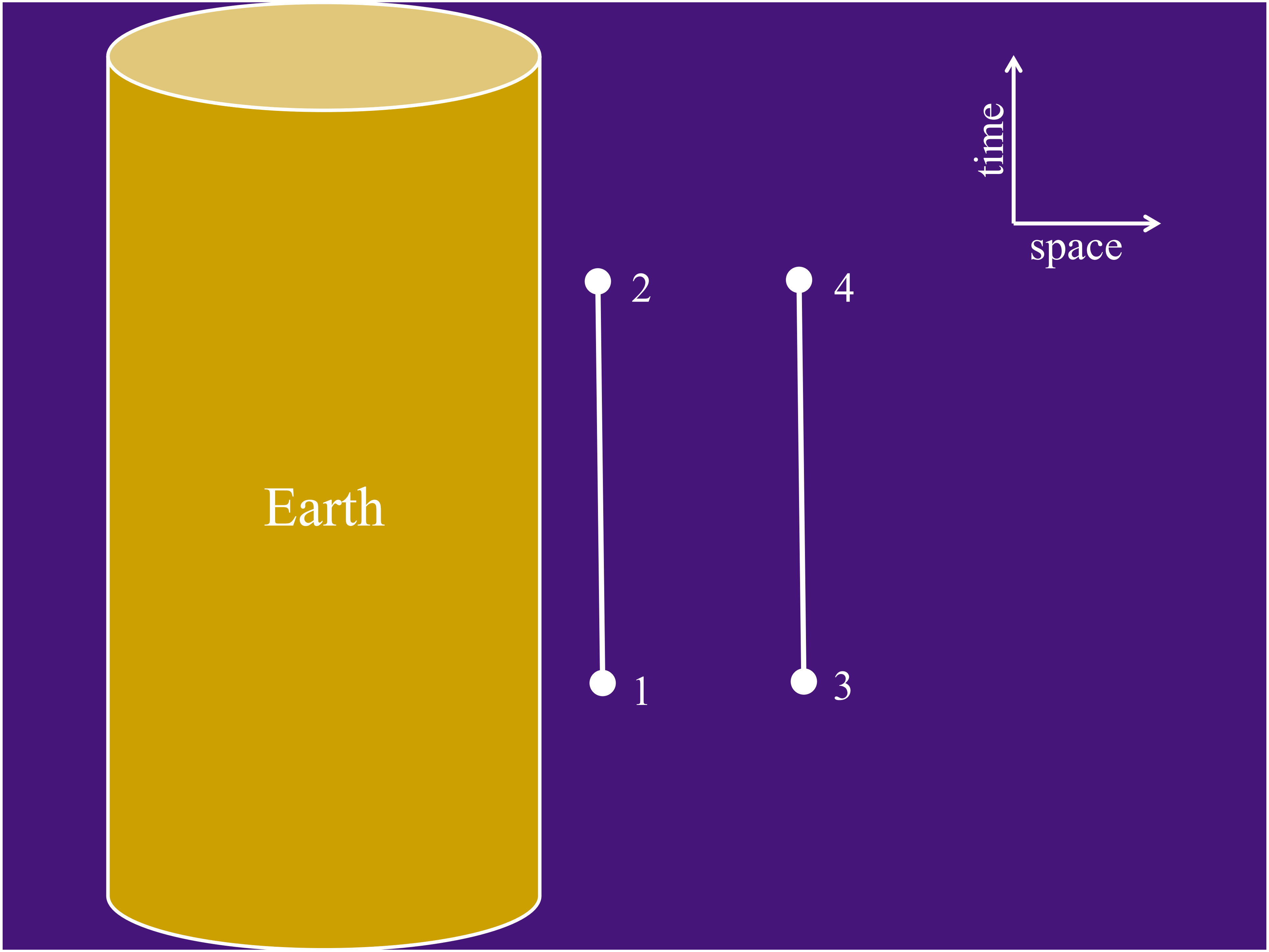
A straight world-line is the path of longest clock-time between two points.

Special relativity: Moving clocks run more slowly.

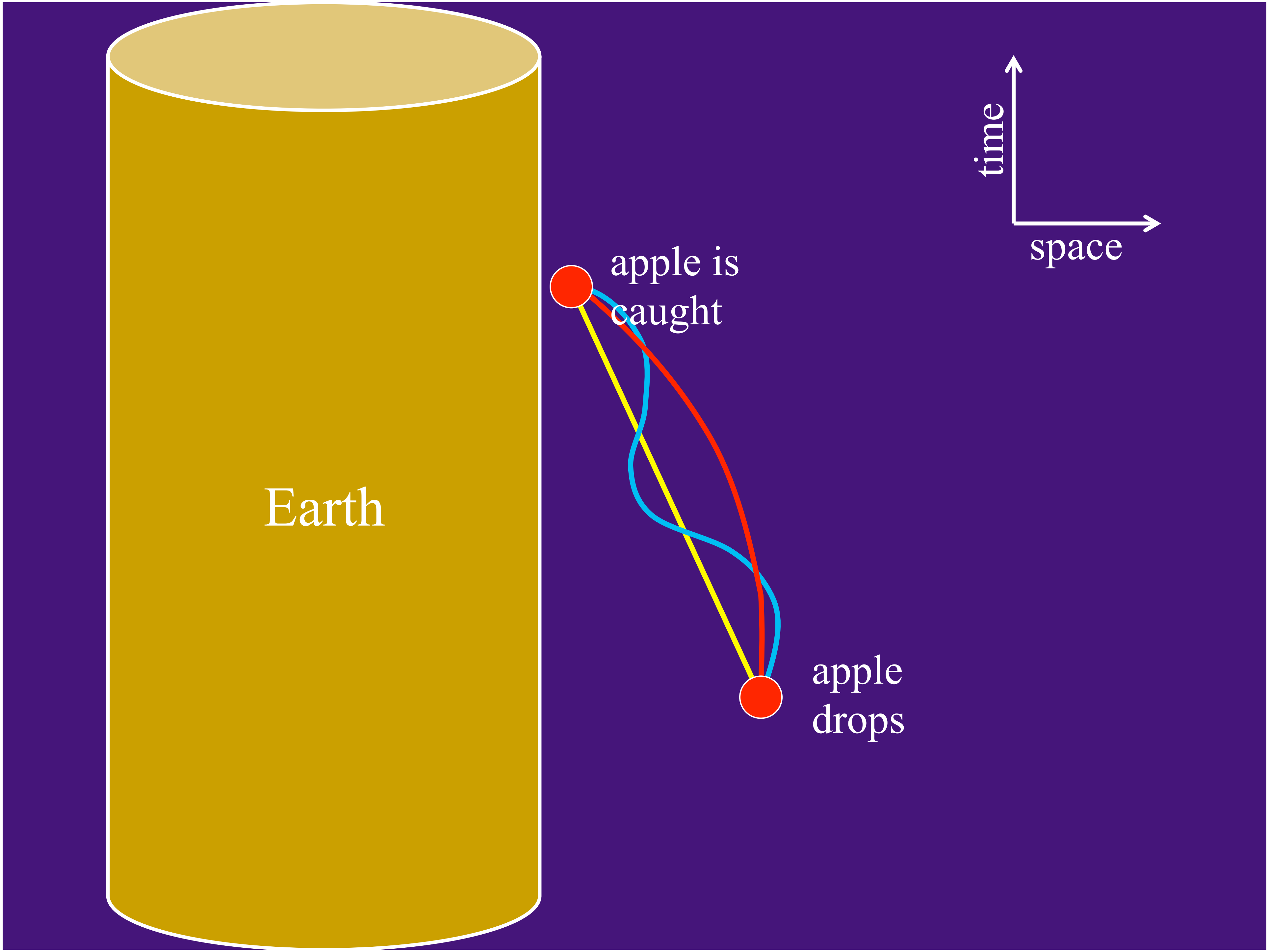


General relativity: Lower clocks run more slowly.

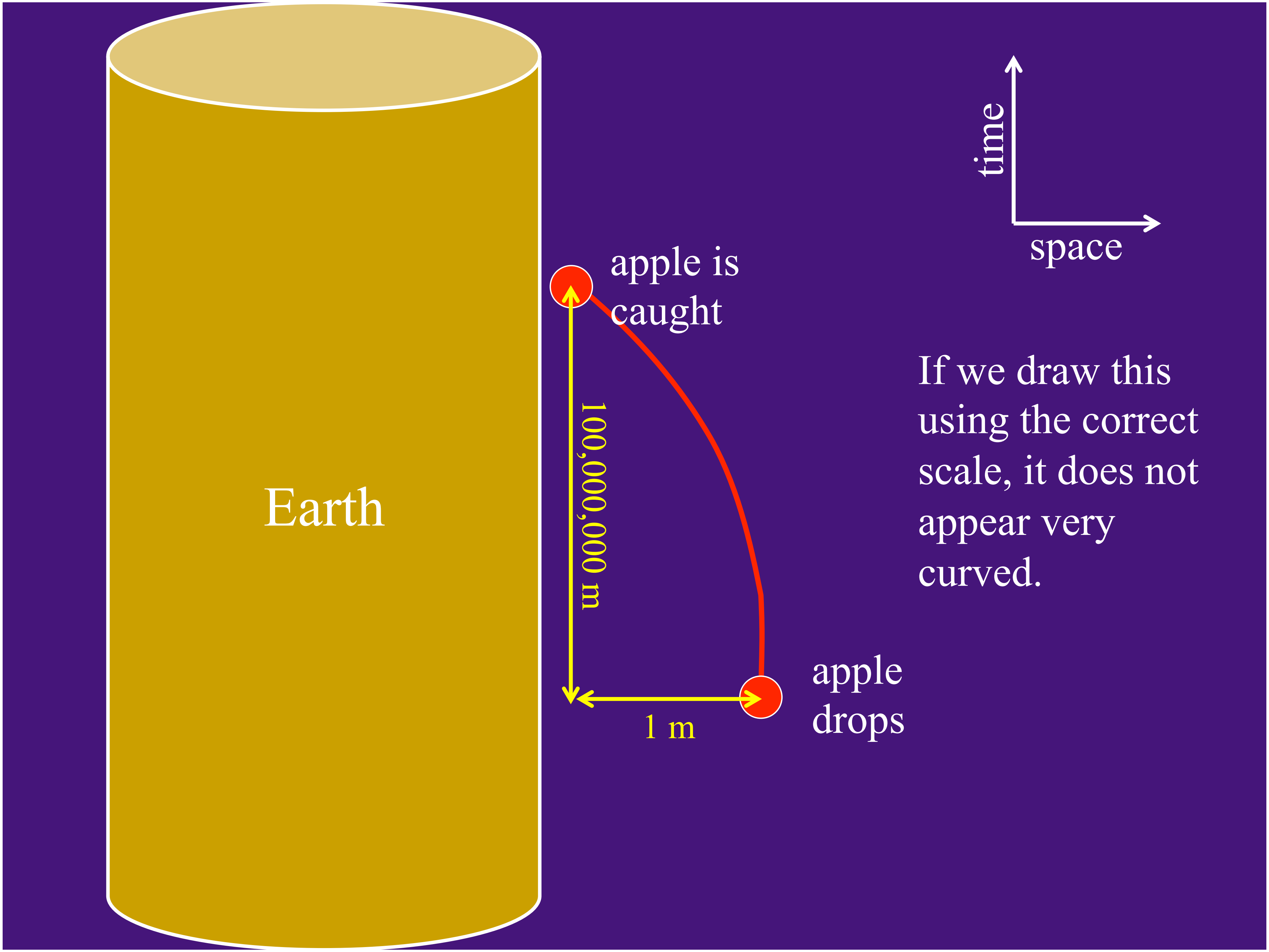




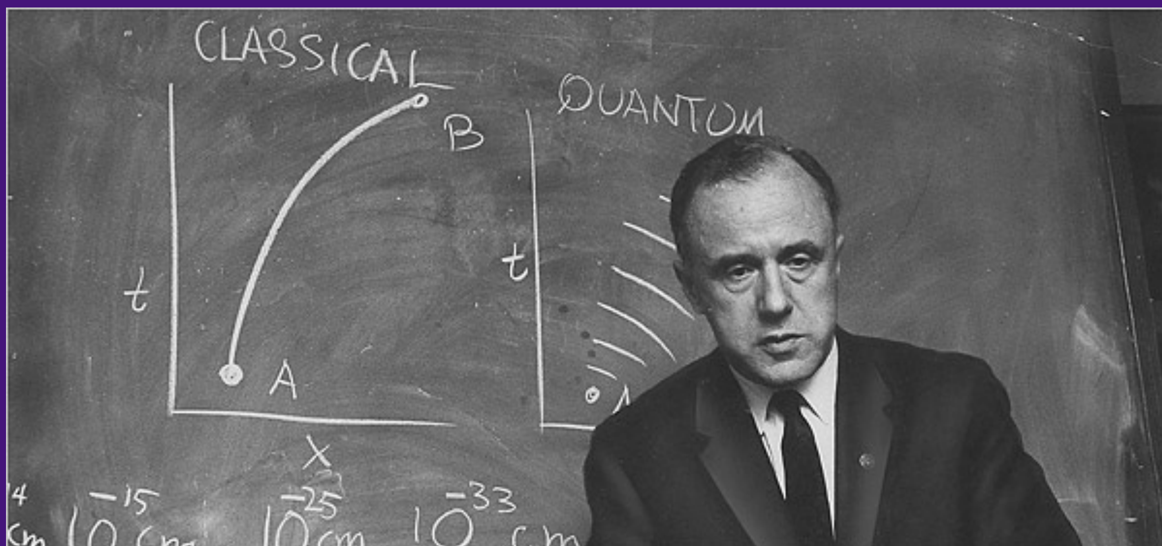
Earth
time
space
2
4
1
3



Earth
apple is
caught
apple
drops
time
space


Earth
apple is caught
apple drops
100,000,000 m
1 m
time
space
If we draw this using the correct scale, it does not appear very curved.

General relativity in brief



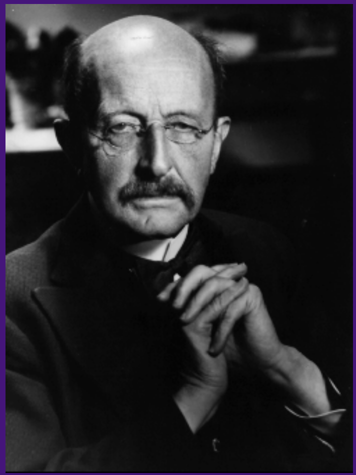
John Wheeler

"Spacetime tells matter how to move.
Matter tells spacetime how to curve."

The next revolution?

- The problem: General relativity is inconsistent with quantum physics.
- At the "Planck scale", our ideas of space and time are very likely wrong.

$$L_P = \sqrt{\frac{\hbar G}{c^3}} \approx 1.6 \times 10^{-35}\ \mathrm{m}$$



Max Planck

What central fact about gravity can guide us toward the next revolution in gravitational physics?

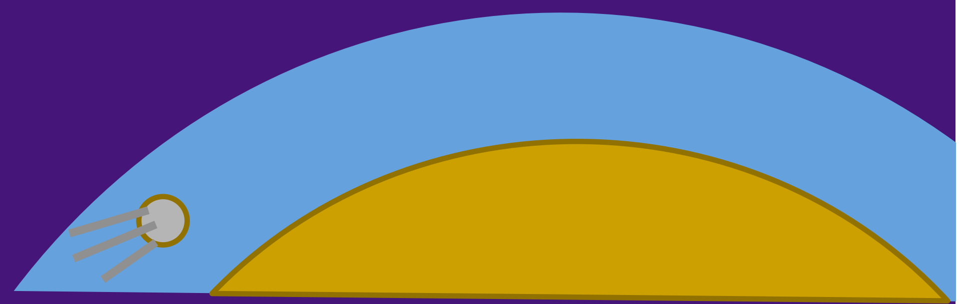
What is gravity?

Something curious
about gravity

Decaying orbits

Q: Satellite in low Earth orbit. Air friction removes some energy from satellite. What happens?

A: Satellite speeds up!



Total loss of energy: $\Delta E = -1000$ J

$\Delta PE = -2000$ J

$\Delta KE = +1000$ J

Many bodies

Virial theorem

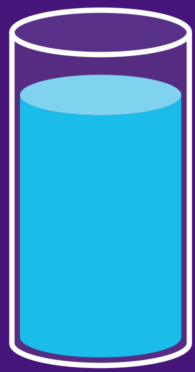
In the long run, on average: 2 KE + PE ≈ 0

Experiment: initial particle speeds are cut by half.

Horizontal traces show KE, E=0, total E, PE

Why this is odd

- Usually, when you add energy to a system, its parts speed up.
- Example: Remove energy from a glass of water. Molecules move slower. Water temperature decreases.
- Now remove energy from a system governed by gravity. Particles move faster. Does the temperature *increase*??



A detour through thermodynamics

Two Laws

The First Law of Thermodynamics

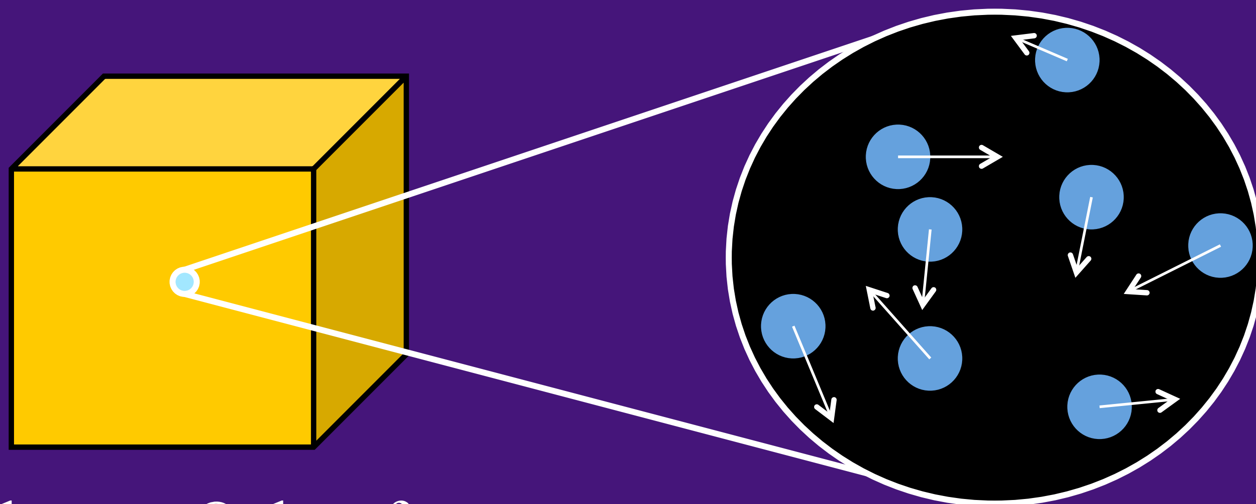
Energy E is conserved. It can change forms, but it cannot be created or destroyed.

The Second Law of Thermodynamics

The total entropy S cannot decrease in any physical process.

What is entropy?

macroscopic
system



We know: Only a few things (volume, energy, composition, etc.)

We don't know: Vast amounts of microscopic detail

Entropy is the amount of information we lack about the microscopic details of the system.

A measure of disorder

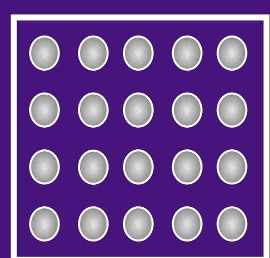
high entropy

low entropy

Order and disorder

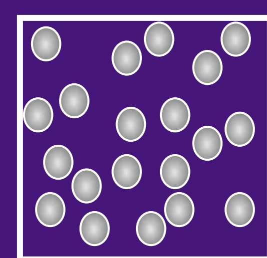
<u>Lower entropy</u>

- crystal
- low T
- unequal T
- small V
- fewer particles



<u>Higher entropy</u>

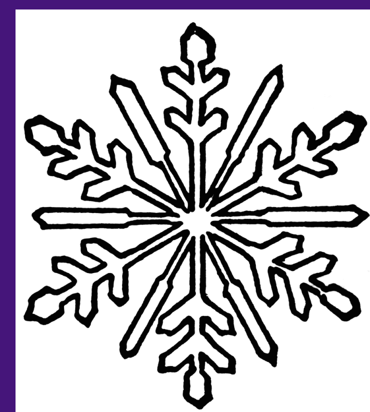
- gas
- high T
- equal T
- large V
- more particles



Snowflakes are impossible?

Snowflake formation: Water vapor (gas) in a cloud condenses into highly ordered ice crystals.

high entropy



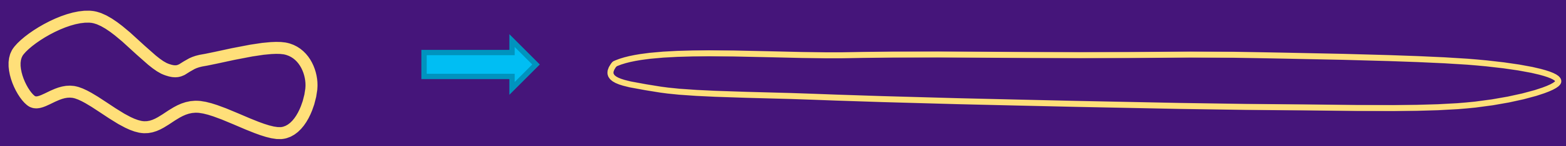
low entropy

How it happens:

Condensation releases heat. Entropy of the surroundings increases! S(final) > S(initial)!

The curious case of rubber bands

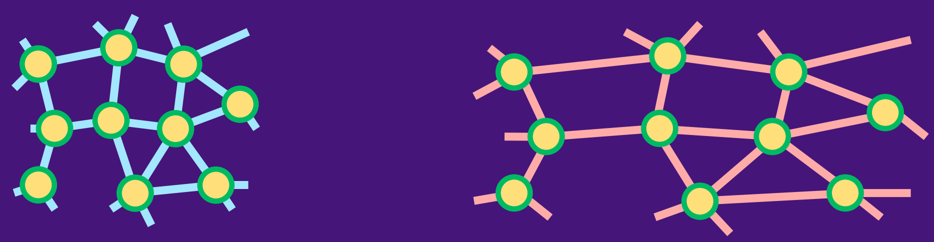
The rubber band



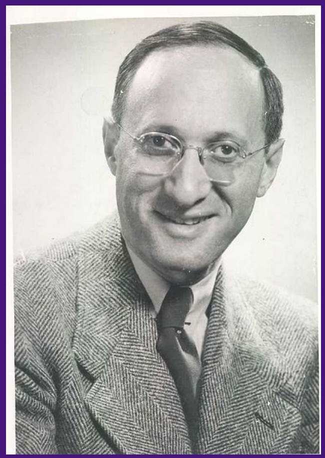
To stretch out a rubber band, we must do work -- that is, we must add energy to it. Why?

Natural hypothesis:

Rubber molecules are held in place by molecular forces. Displacing them means we have to add molecular potential energy.

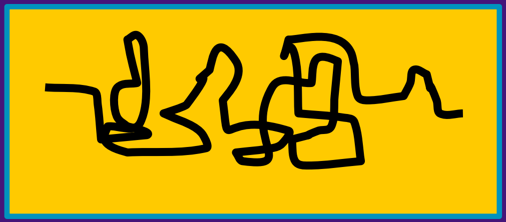


Polymer entropy



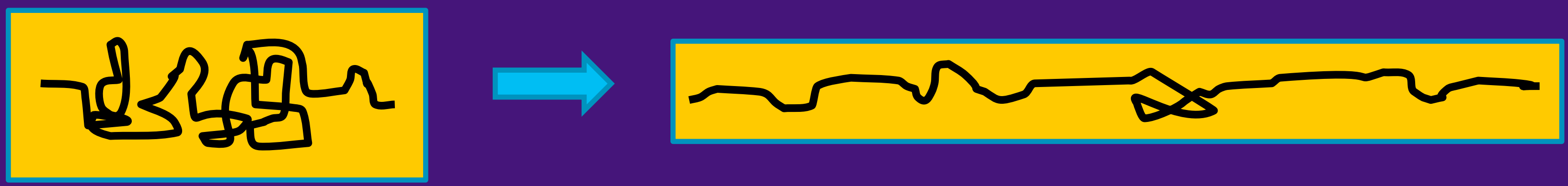
Eugene Guth

- Rubber is made of long polymer molecules, which are very tangled up in the material.
- Tangled and untangled states of the polymer have essentially the same energy.
- Tangled polymer states have a higher entropy.



Typical polymer configuration in rubber

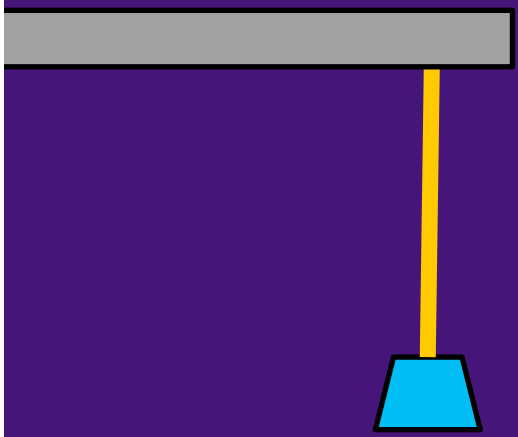
Stretching the rubber band



- Stretching a rubber band reduces polymer entropy.
- However, total entropy cannot decrease.
- We must add energy to the rubber band to heat it up!

Moral: Entropy differences *by themselves* can give rise to forces. (Microscopic details are complicated.)

A thought-experiment

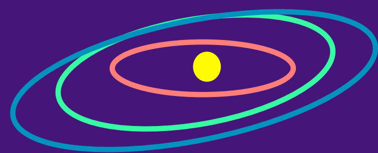


- Hang a weight from a rubber band.
- Heat up the rubber band (use a hair dryer).
- Does the hanging weight go up or down? That is, does the rubber band grow or shrink?

Gravity and entropy

How to form a solar system

Large, sparse, cold
(uniform 10-20 K)

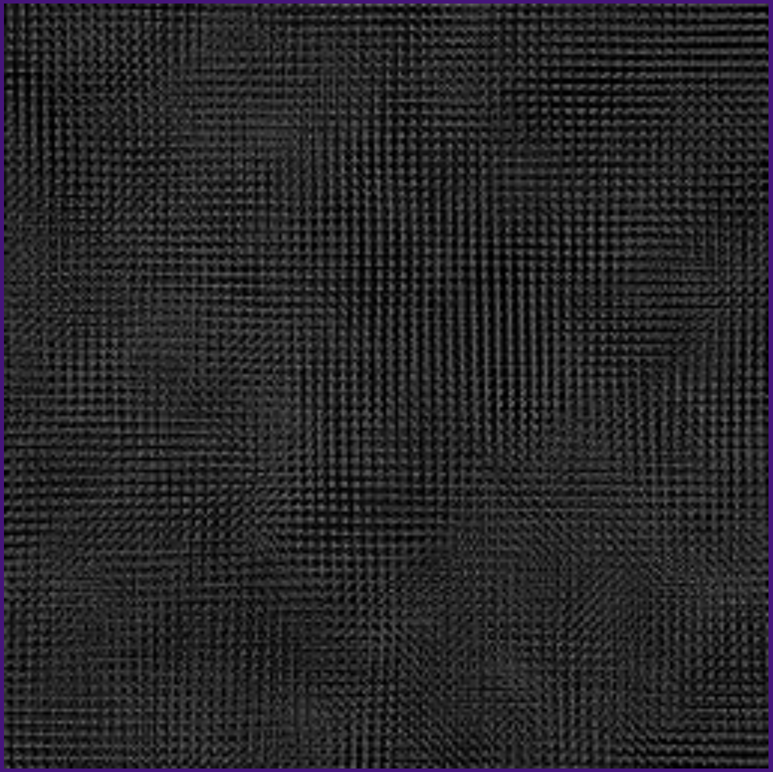


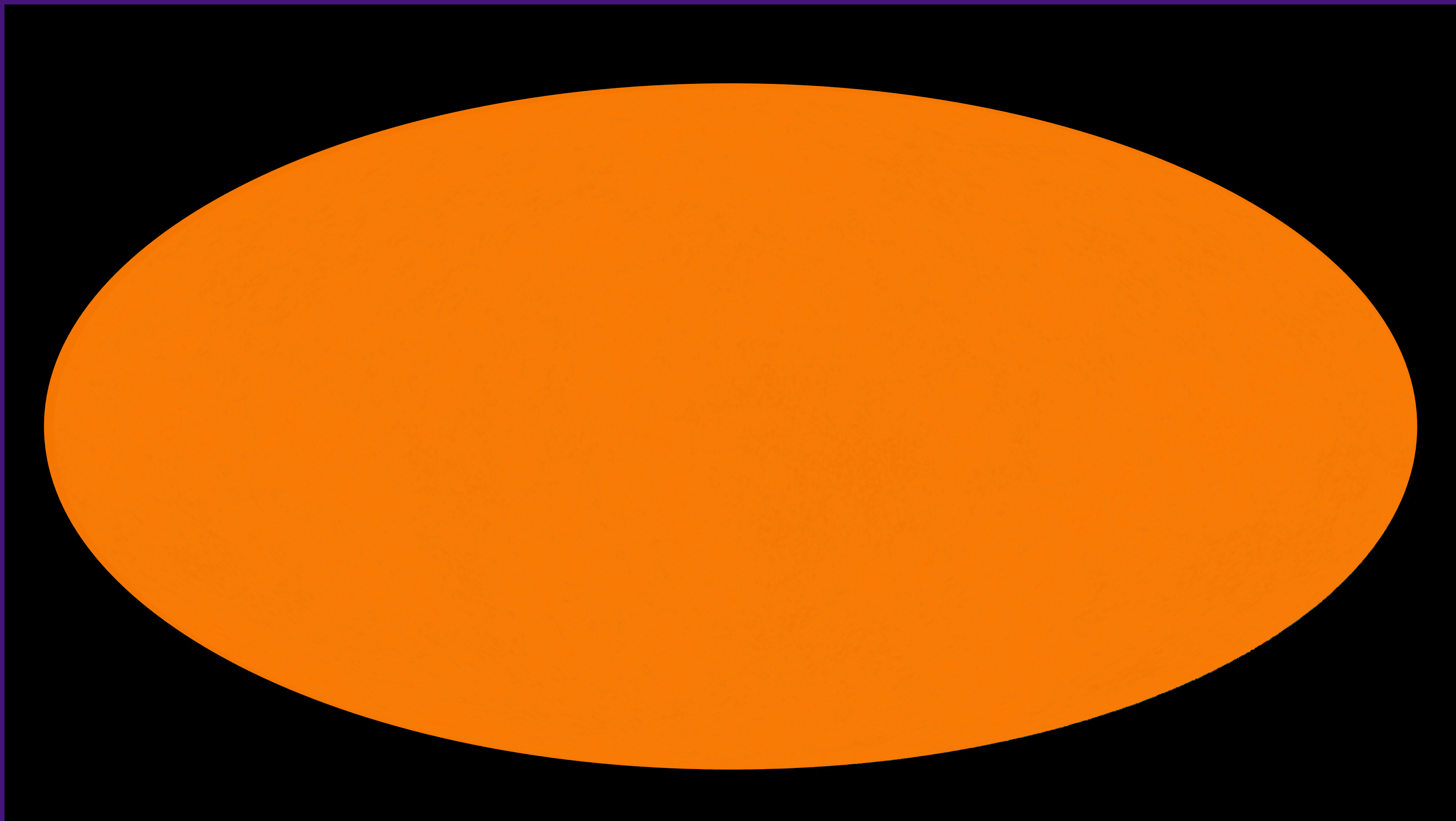
Compact, highly non-uniform in density and temperature

Secret ingredient: Gravity!

For large systems dominated by gravity, the Second Law of Thermodynamics favors "clumpiness"

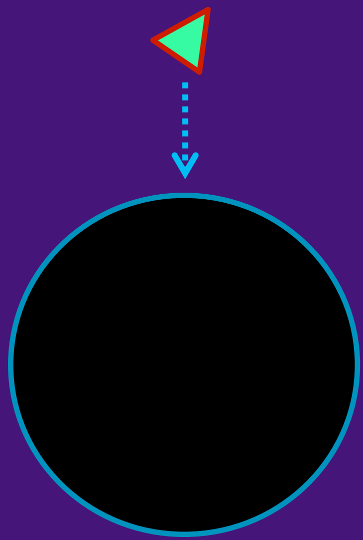
The formation of just about everything





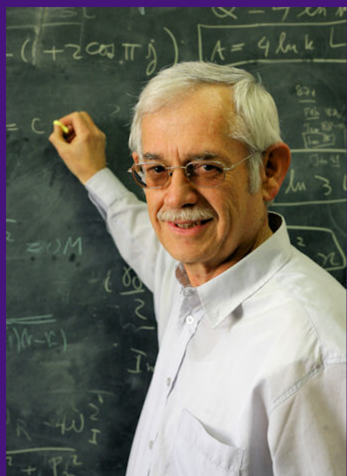
Gravity is the ultimate source of order in the Universe.

A problem about black holes



- Black holes are extremely simple objects -- no observable properties except their mass, charge, angular momentum.
- No information can escape from within the event horizon of a black hole.
- Drop something into a black hole. Where does its entropy go?
- Does a black hole have entropy?

Bekenstein's conjecture



Jacob Bekenstein

- Hand-waving quantum arguments suggest that black holes do have entropy.
- Entropy = information lost in the black hole (history, composition, etc.)
- Black hole entropy formula

$$S \ (\text{bits}) \sim \frac{A_{bh}}{L_P^2}$$

The black hole area theorem

Q: Two or more black holes interact, collide, merge. What happens?

A: Lots of extremely complicated stuff!

<u>Area theorem</u> (Hawking):

The sum of the horizon areas of all the black holes in a system can never decrease.

A skeptical response

Stephen Hawking

- First reaction: Bekenstein must be wrong!
- If black holes have both energy and entropy, they must also have non-zero temperature.
- But black holes cannot transfer heat to anything at a lower temperature.
- What's needed: A much more sophisticated quantum calculation!

Surprise, surprise!

Stephen Hawking

- Hawking finds: Bekenstein is right!
- When we take quantum effects into account, black holes are not quite black! They emit thermal radiation!
  - Black hole temperature: Very low
  - Black hole entropy: Extremely high

+ energy → T_{bh} is *lower*

How much entropy is a lot?

<u>The Sun</u>

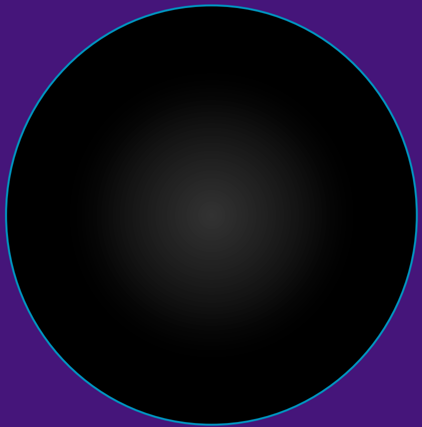
- Radius: 700,000 km
- Entropy: $S \sim 10^{59}$ bits

<u>Solar-mass black hole</u>

- Radius: 3 km
- Entropy: $S \sim 10^{78}$ bits

A remarkable connection

- Area is a geometrical property of a black hole.
- Entropy is about missing information.
- Gravity and quantum physics make a connection between geometry and information.



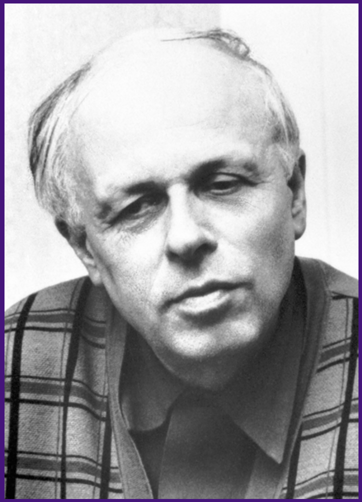
Event horizon is a one-way surface for information

Sheer speculation

The way forward?

What if gravity is not fundamental?

Idea: Macroscopic gravity arises from some microscopic physics we don't (yet) understand -- gravity is a thermodynamic aspect of the underlying interactions.



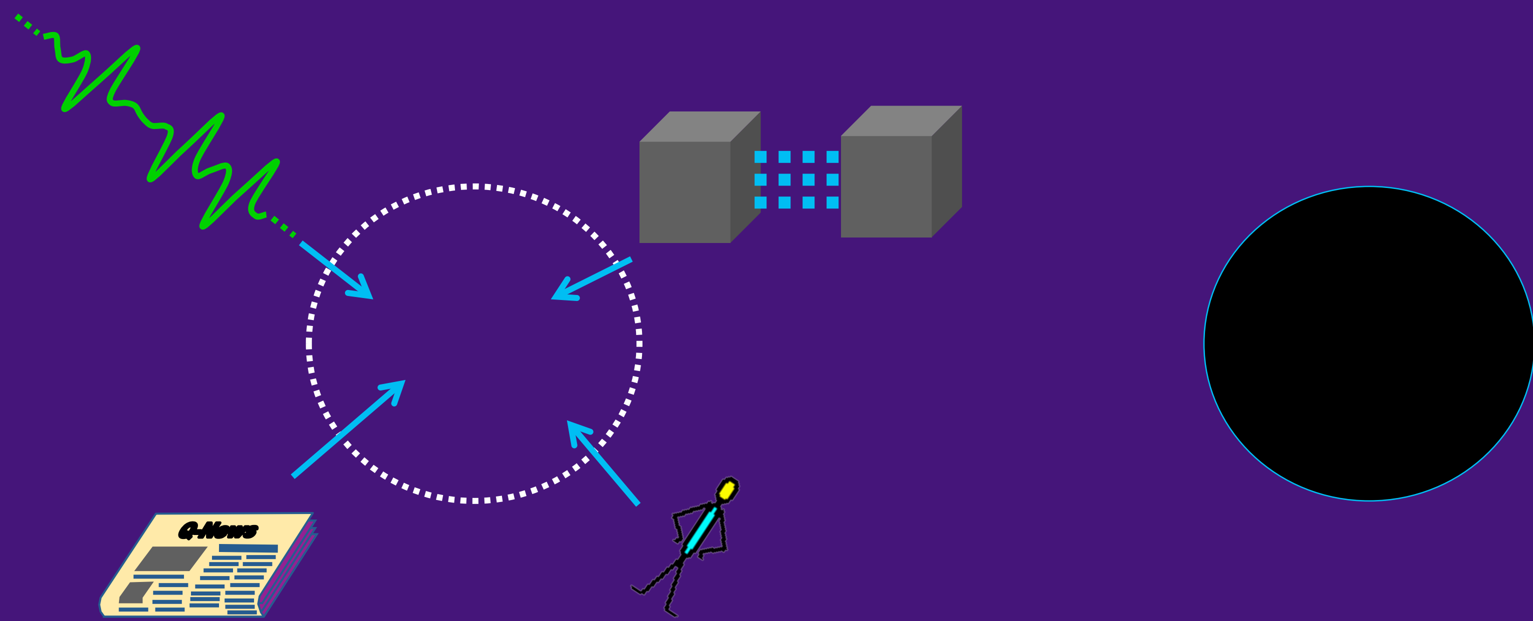
Andrei Sakharov

Gravity is an emergent property analogous to the elastic properties of solids.

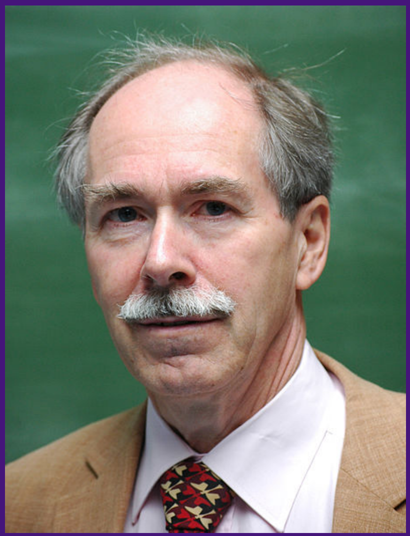
Information and area

Bekenstein:

Black hole entropy is the upper limit to the amount of information that can be stored in a bounded region of space.



The Holographic Principle

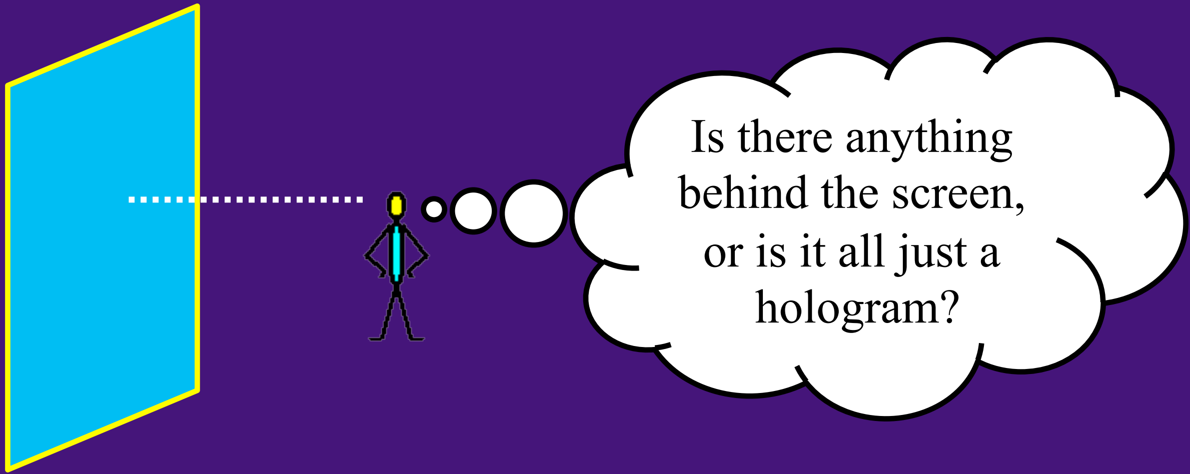


Gerard t'Hooft

Maybe what is true of event horizons is true of any bounding surface.

Where does the information of a room reside? Two possible answers!

- Within the volume of the room
- On the outer surface of the room

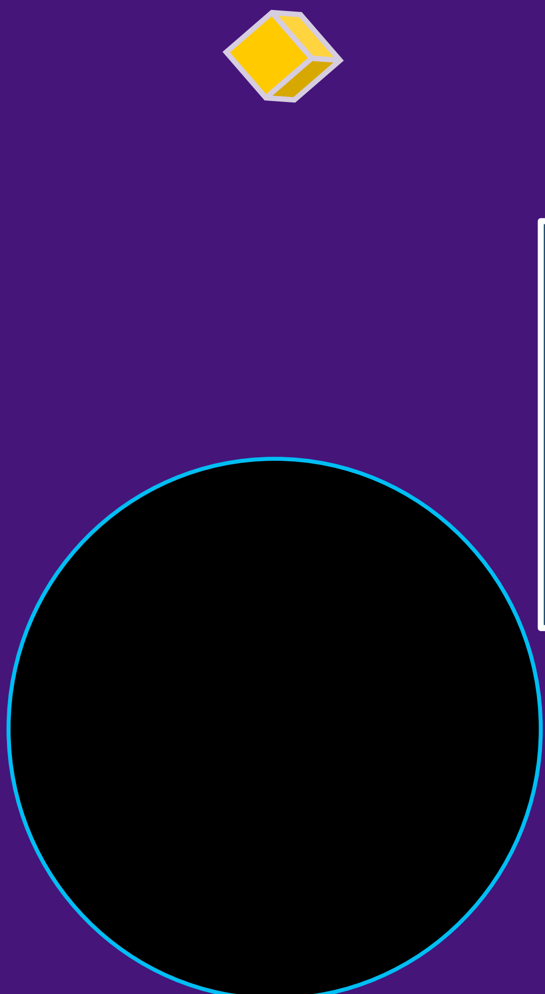


What is gravity?

Erik Verlinde

- New idea: Gravity is an entropic force, like the elastic pull of a rubber band.
- When masses are close together, the entropy is greater -- this entropy difference by itself leads to an apparent force.
- General relativistic view: Entropy differences lead to the curvature of spacetime. (Information → geometry.)

Object near a black hole



- Object approaches the event horizon of a black hole. But it does not disappear all at once.
- akes object harder to tside the black hole.
- ns to interact with tmosphere" of the

Lost information

↓

Entropy increase

↓

Attractive "force"

- Outside observer begins to lose some information well before the particle crosses the horizon.

The next revolution?

Probably not. (Most new ideas are wrong.)

Many other interesting competing ideas: string theory, d-branes, loop quantum gravity.

We do not have much experimental data to guide us -- even Hawking radiation is still only theory!

Good news:

- Being wrong can still be useful.
- Entropic gravity is being built on a insights about gravity -- like Einstein's previous revolution.

Finis