Space, Time, & Relativity

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Space & Time form the framework and backdrop for everything in our lives. But does reality match our intuition? How does modern physics describe space & time? This lecture will provide an overview and a common set of core concepts - then we can explore topics in more depth during the question/discussion time.

Major Topics

- Measuring space (distance), time, and motion
- Basic concepts of special relativity
- Basic concepts of general relativity
- (briefly) Quantum gravity - is spacetime made up of “pixels”?

We're so familiar with the concepts of space and time that it can be very difficult to really understand them and question our preconceptions...

"To see what is in front of one's nose requires a constant struggle."

- George Orwell

Core concepts for how we experience events in the world:

Space - How much distance separates 2 events (how many rulers to cover the distance?)

Time - How many "ticks" of a clock must we wait after one event, before the next event happens?

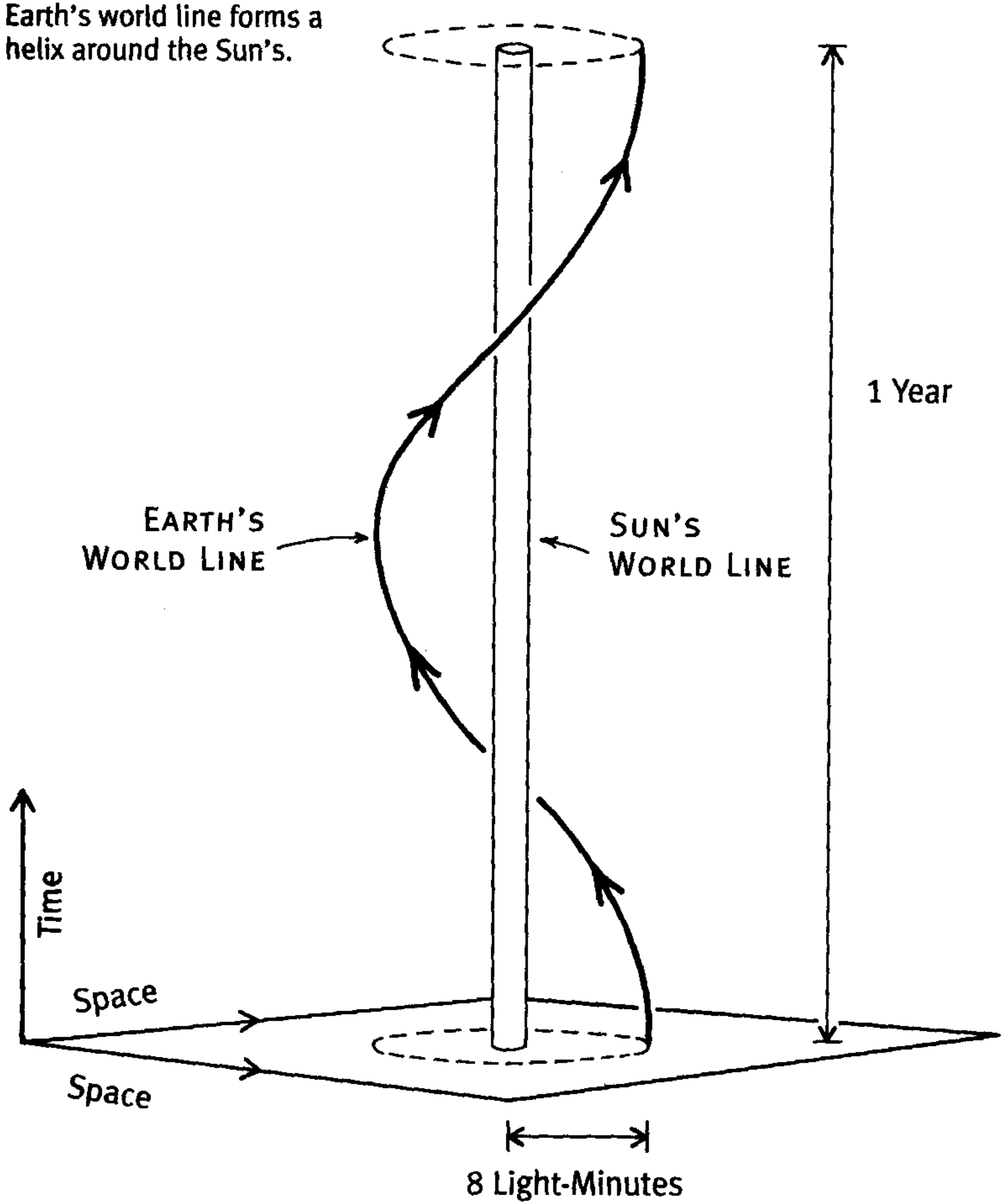
Motion - Amount of space traversed in a certain amount of time (intuitively, we know space and time are related...)

Reference Frames & Space-time Diagrams

Question: How many coordinates do I need in order to specify the location of any event?

Answer: 4 (consider what information you needed in order to be present at the start of this lecture)

Note that the specific coordinates depend on the reference frame you use.



Space-time diagrams - a way to visualize events in our experience

(From J.R. Gott, *Time Travel in Einstein's Universe*, p. 9)

Core Concepts of Special Relativity

- Principle of Relativity - Laws of nature are the same for all observers in uniform motion (e.g. if F=ma when F, m, & a are measured from your point of view, then the same equation will work for me when I measure these quantities from my perspective). No experiment can decide which observer is "really" moving.

- (As a consequence) Speed of light is the same for all observers

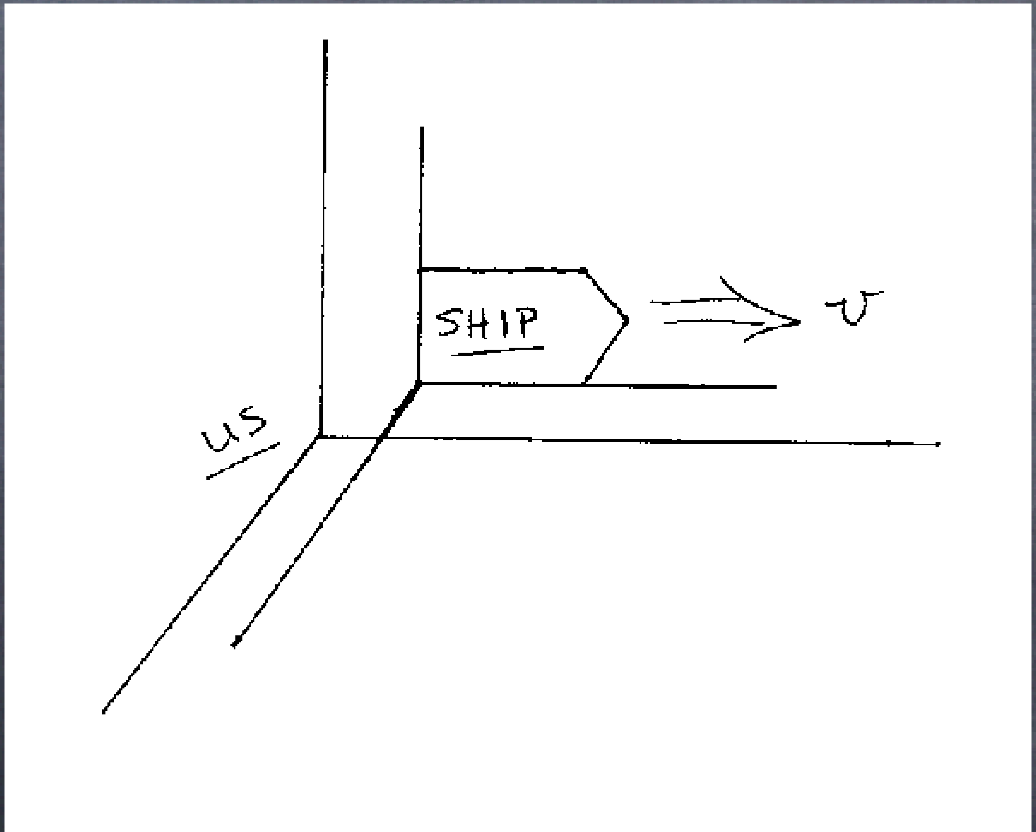
  - Absorb what this means - if you are moving relative to me, and we both observe the same light beam, we both see it moving at the speed of light (c) relative to us!

Once you really believe that the speed of light is the same for all observers, the strange consequences of special relativity (time and length contraction, etc.) follow as purely logical consequences. The core conceptual difficulty is in really absorbing and taking seriously that everyone measures the same speed of light ($c \sim 300{,}000$ km/second), and following that idea through to its consequences.

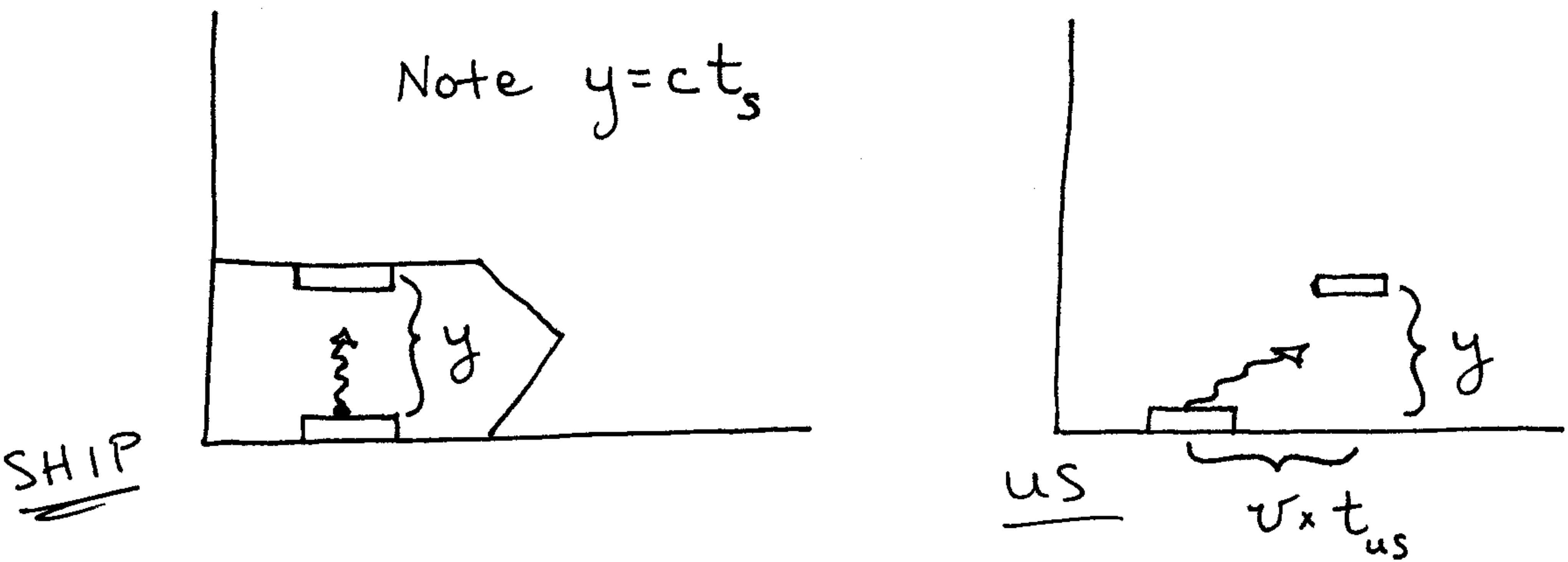
Implications of an invariant speed of light...

Question: How do distances and times between events as measured by one observer relate to those measured by another?

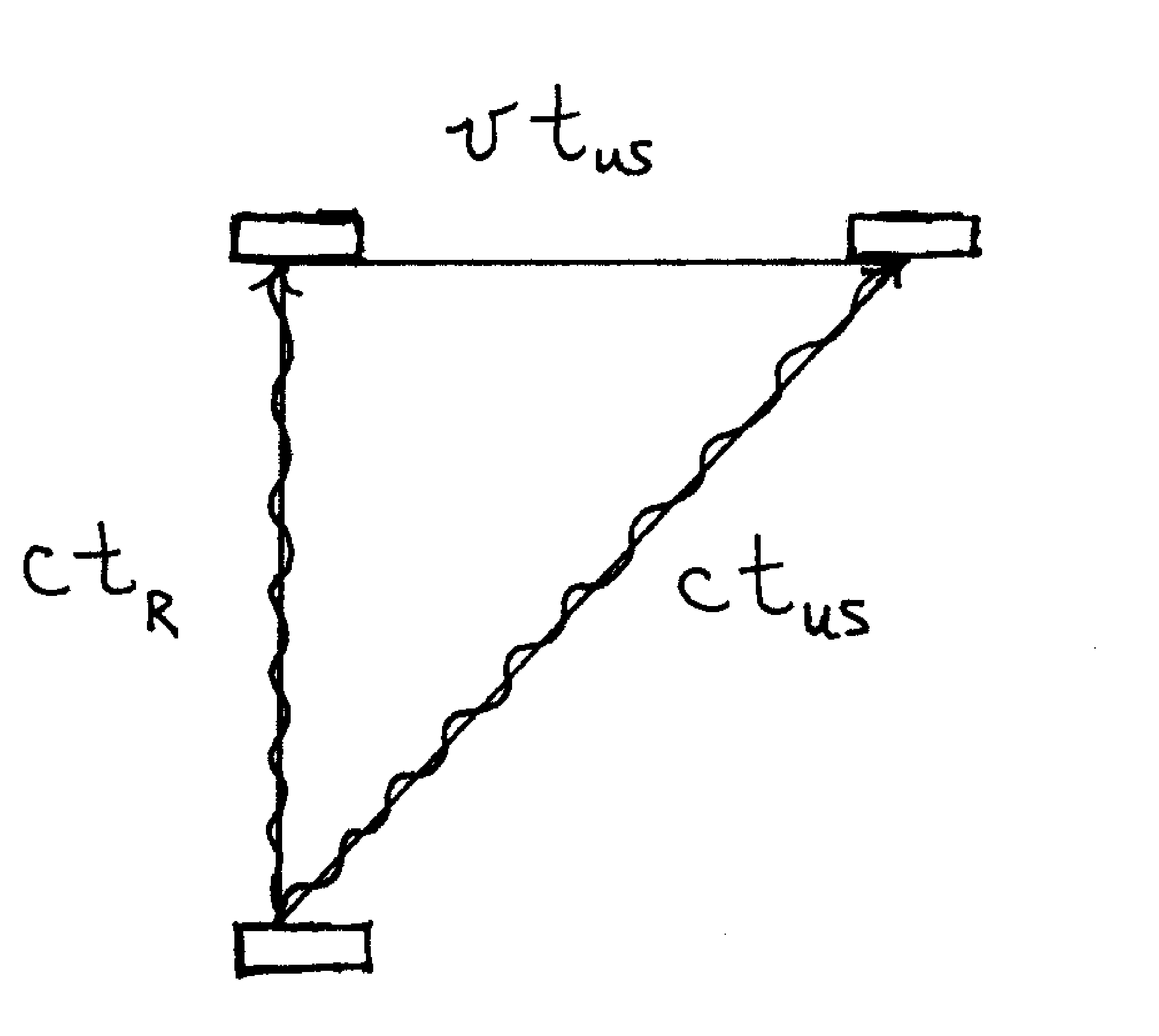
To answer this, consider 2 reference frames - “us” and “spaceship” (non-accelerating, just drifting in space at speed v)



Light clock - travel of a light pulse between 2 mirrors is the "tick" of the clock (2 events are "light leaves the bottom mirror" and "light hits the top mirror")



Compare what the path of the same light pulse looks like in the two reference frames:



Result: Transformation relating time as we measure it to time as measured in the ship:

Pythagorean Theorem:

$$(ct_s)^2 + (v\,t_{us})^2 = (c\,t_{us})^2$$

$$\Downarrow$$

$$\boxed{t_{us} = \frac{t_s}{\sqrt{1-\left(\frac{v}{c}\right)^2}}}$$

Interpretation...

Why does this happen?
Light pulse must travel farther in our reference frame than it does in the ship frame. But we're insisting that the speed of light be the same for both of us (our distance divided by our time must be the same number as ship distance divided by ship time). So we've backed ourselves into a corner: Traveling a longer distance at the same speed must take more time.

We share 2 events in common: (1) "light leaves bottom mirror" and (2) "light hits top mirror". The time between these 2 events is longer for us than it is for a passenger on the ship.

What if we're not moving at constant velocity?

Special relativity applies only for non-accelerating observers in the absence of significant gravitational fields. To add these things, we need a general theory of relativity...

Core Concepts of General Relativity

- Inertia - undisturbed particles have a preferred state of motion, and resist changes to that state of motion
- Principle of Equivalence - uniform acceleration cannot be distinguished from a uniform gravitational field
- Space-time is curved - distribution of matter and energy shapes the space-time fabric through which things move ("matter & energy tell space-time how to bend, space-time tells matter and energy how to move")

Inertia

The natural tendency of objects to follow certain paths ("geodesics") through space-time, unless there is some force acting on the object. (These paths are straight lines at constant speed in "flat" space-time.)

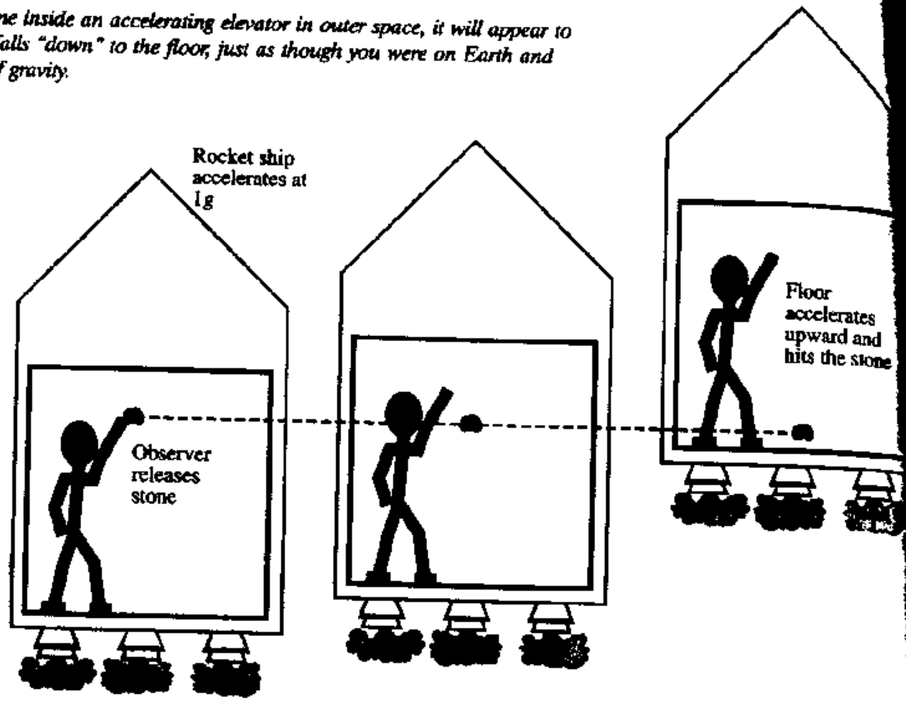
Objects resist changes to their natural state of motion. The amount of resistance is one measure of their mass ("inertial mass" - how much resistance you feel when you try to push something).

Question: Why do different objects fall with the same acceleration? (Why is gravitational mass exactly equal to inertial mass?)

Answer of GR: Gravity is not really a force - it is a consequence of the curvature of space-time.
(Their inertia causes them to follow natural geodesics, but these are no longer straight lines).

Equivalence of gravity & acceleration

Figure 11.7
If you release a stone inside an accelerating elevator in outer space, it will appear to you that the stone falls "down" to the floor, just as though you were on Earth and feeling the effects of gravity.



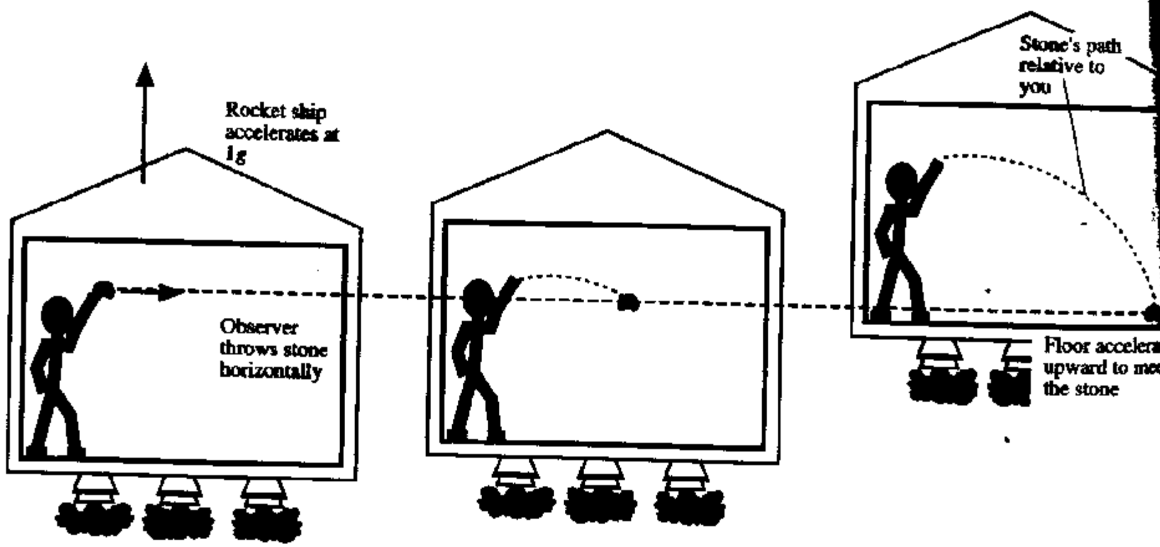
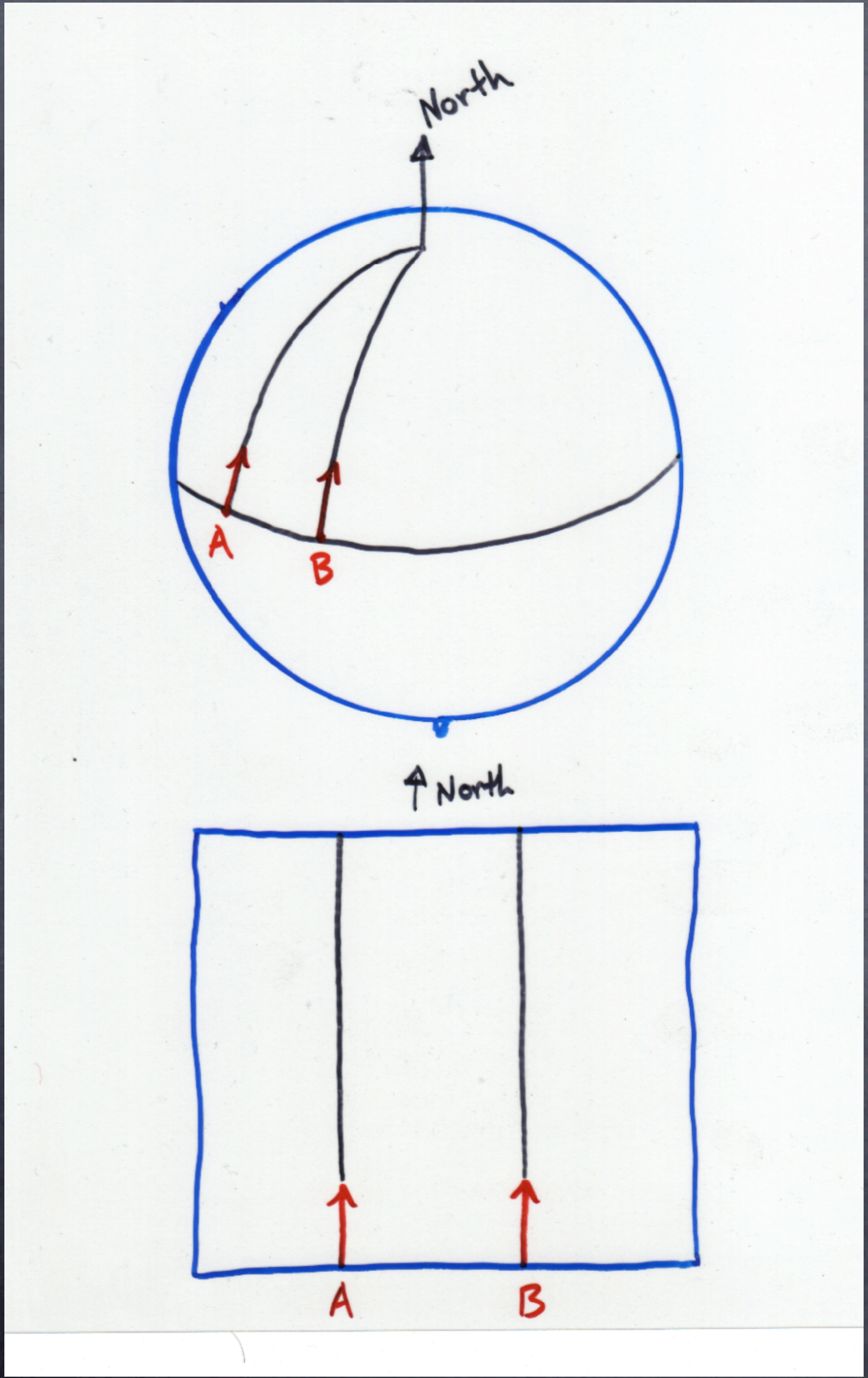


Figure 11.8
If you throw a stone inside an accelerating elevator in outer space, it will appear to you that the stone falls to the floor as though you were on Earth and feeling the effects of gravity.

(From Art Hobson, *Physics: Concepts and Connections,* p. 296)

Curved Space in 2 dimensions



Quantum Gravity

Is space-time truly continuous, or is it grainy at a very small scale? (like an image on a computer screen). Is there a smallest possible distance and a smallest possible time?

Current thinking suggests there should be, on the Planck scale: 10^{-33} cm and 10^{-43} sec.