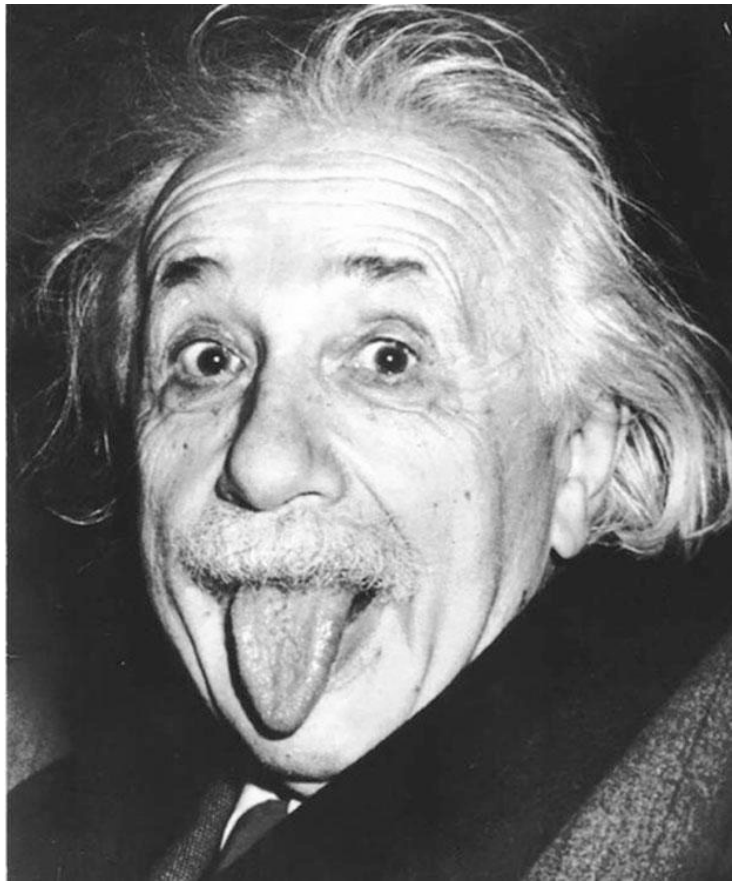
Einstein's Relativity: Shattering our Everyday Notions of Time



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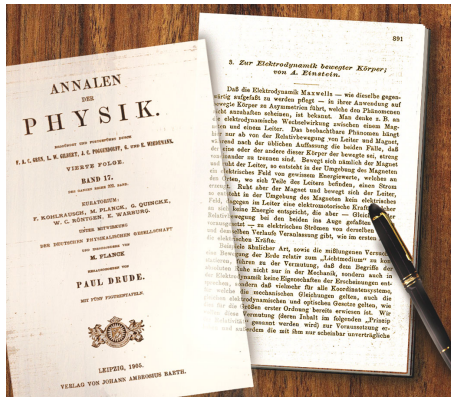
Governor's School for the Sciences and Engineering (GSSE) Lecture
University of Tennessee, Knoxville
June 20, 2023

A Little History
A Quick Overview

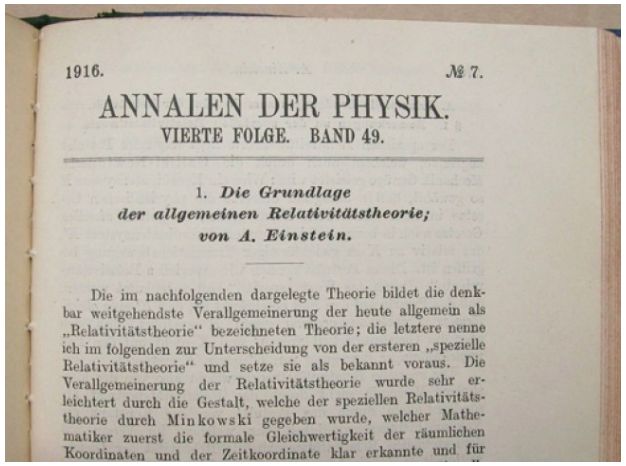


1905 – Annus Mirabilis

Einstein develops his "Special" Theory of Relativity

- Considers *uniform* relative motion – i.e., relative motion at constant speed – involving two observers.
- Time and distance between any two events observed by the two observers will not be the same.

☞ *Tells us that time and space are relative.*
☞ *Points us to the concept of spacetime.*

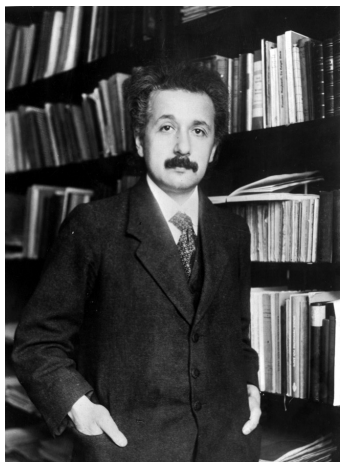

1916. № 7.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie; von A. Einstein.*

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für



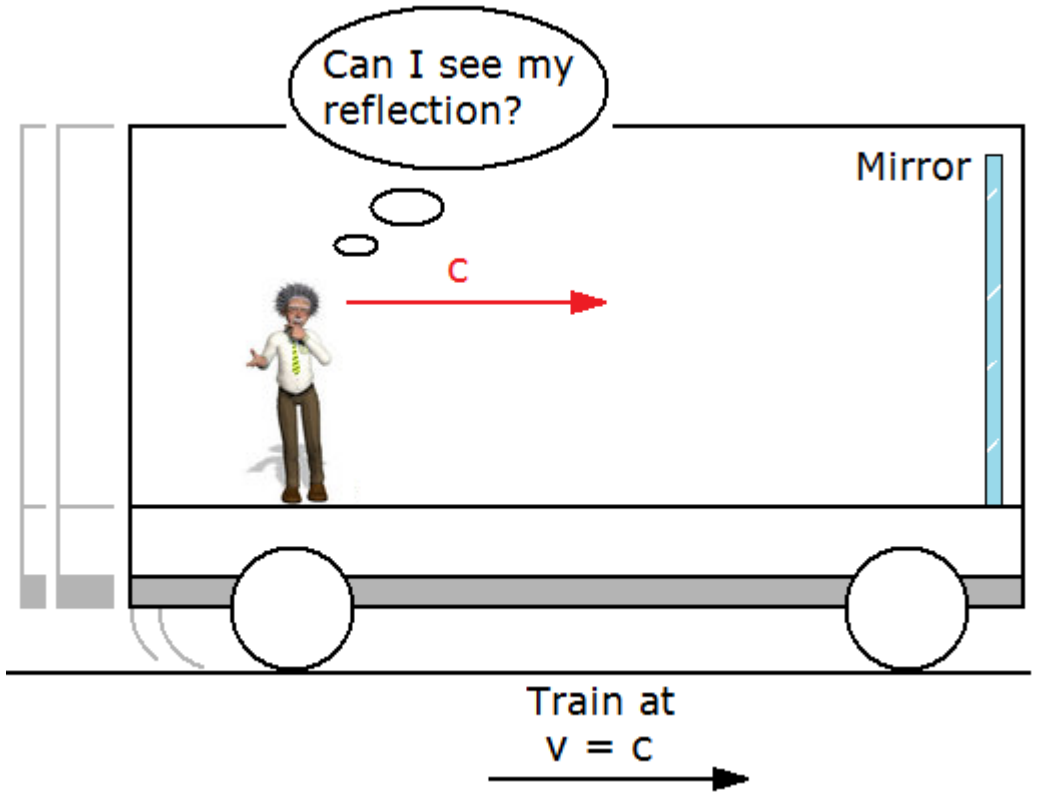
1916

Einstein publishes his "General" Theory of Relativity

- Considers *all* relative motion – i.e., uniform and accelerated motion – involving two observers.
- Ties acceleration to gravity and gravity to spacetime.

☞ *Tells us that spacetime is curved.*
☞ *Tells us that what we perceive as gravity results from the curvature of spacetime.*

Thought Experiment: Speed of Light



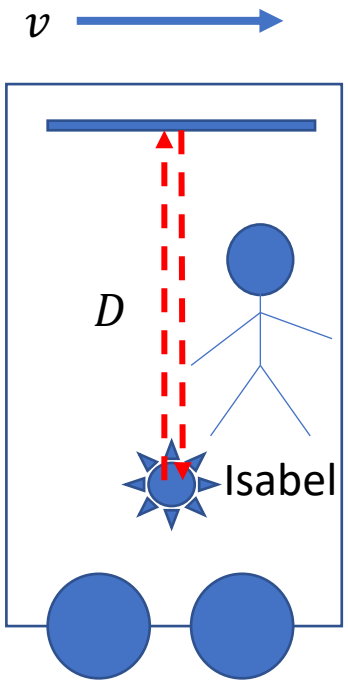
Thought Experiments: Einstein's MO, Einstein's Genius

Reaped profound implications from very simple experiments.

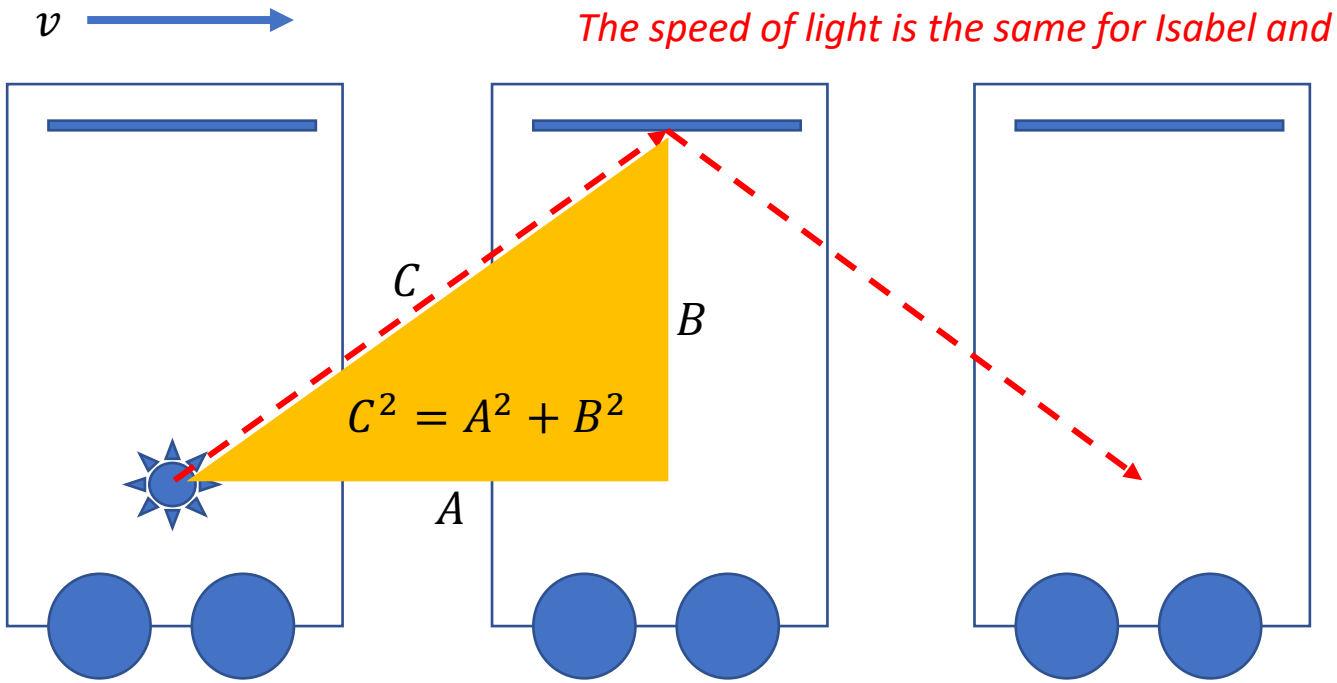
$$\frac{v + c}{1 + \frac{vc}{c^2}}$$

Thought Experiment: Time

Postulate 2:
The speed of light is the same for Isabel and Noah.



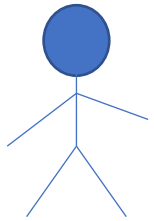
$$\Delta t' = \frac{2D}{c}$$



$$\left(\frac{c\Delta t}{2}\right)^2 = D^2 + \left(\frac{v\Delta t}{2}\right)^2$$

Time Dilation

Two Events:
- Emission of Light
- Detection of Light



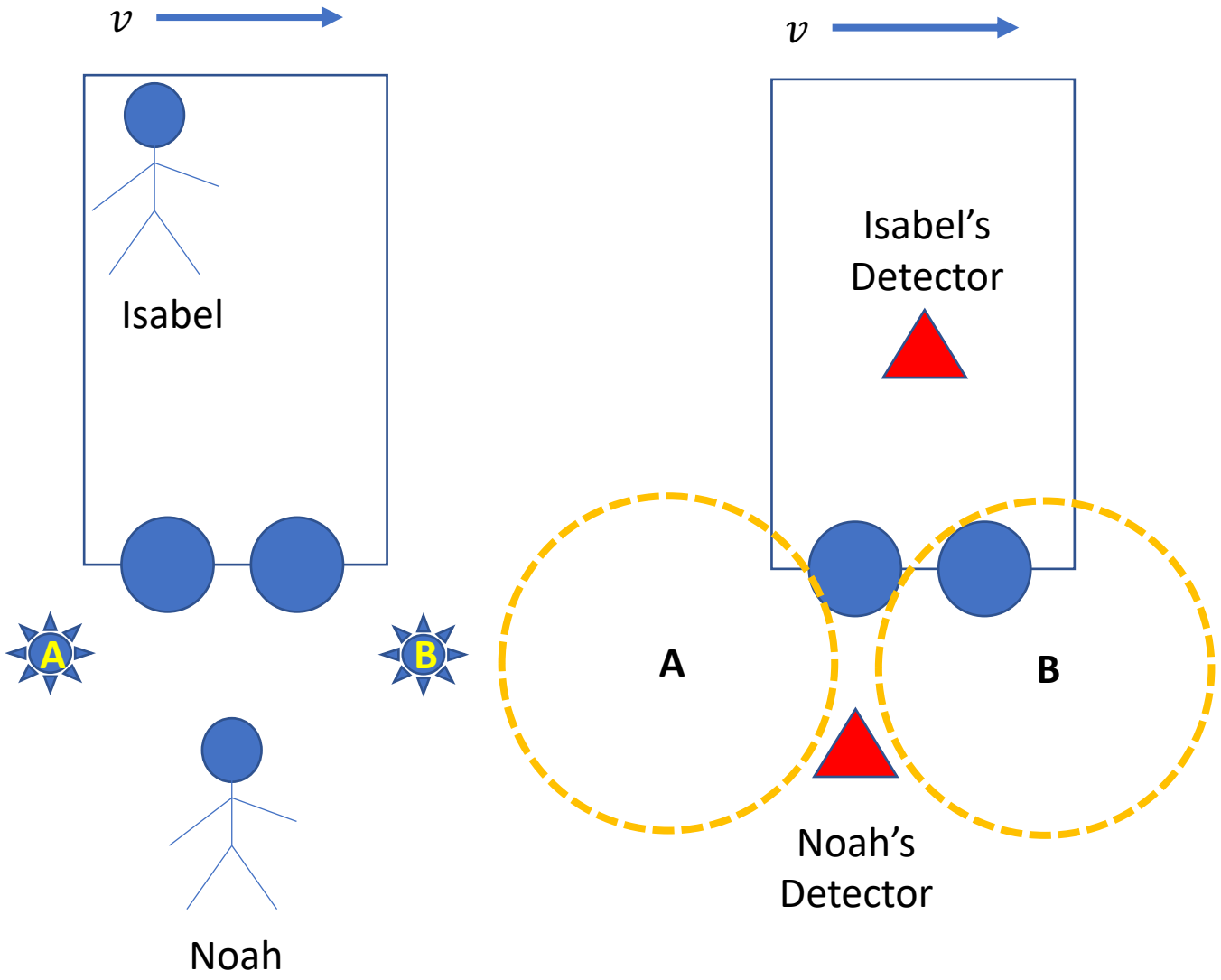
$$\Delta t = \frac{2D}{c\left[1 - \left(\frac{v}{c}\right)^2\right]^{\frac{1}{2}}} = \frac{\Delta t'}{\left[1 - \left(\frac{v}{c}\right)^2\right]^{\frac{1}{2}}}$$

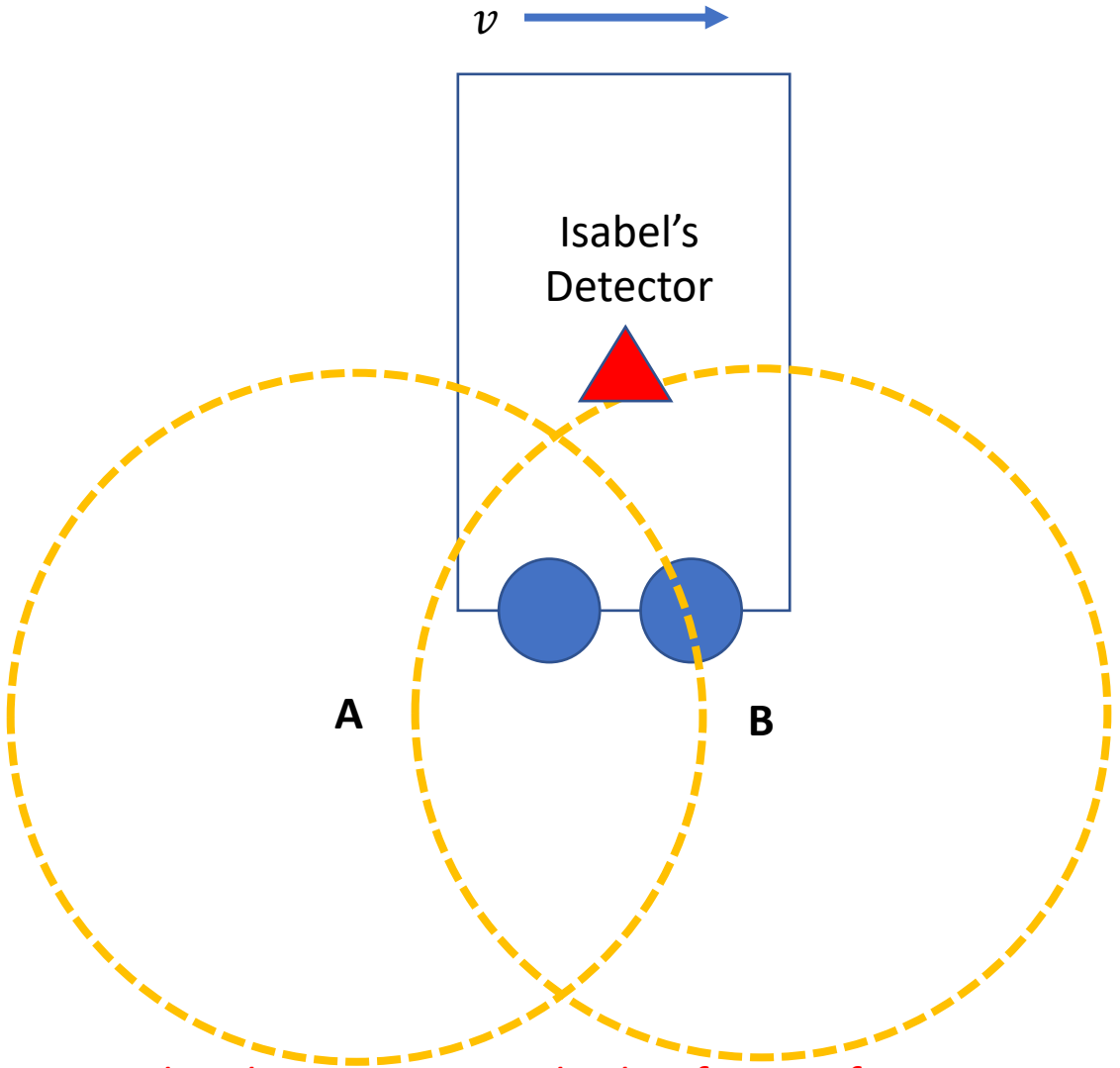
$$\Delta t > \Delta t'$$

Noah and Isabel will not agree on the duration of time between the two events. Isabel's clock is running slow relative to Noah's.

Thought Experiment: Simultaneity

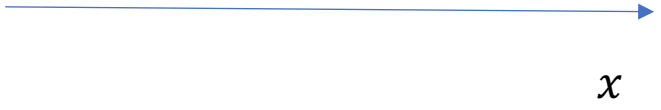
Postulate 2:
The speed of light is the same for Isabel and Noah.



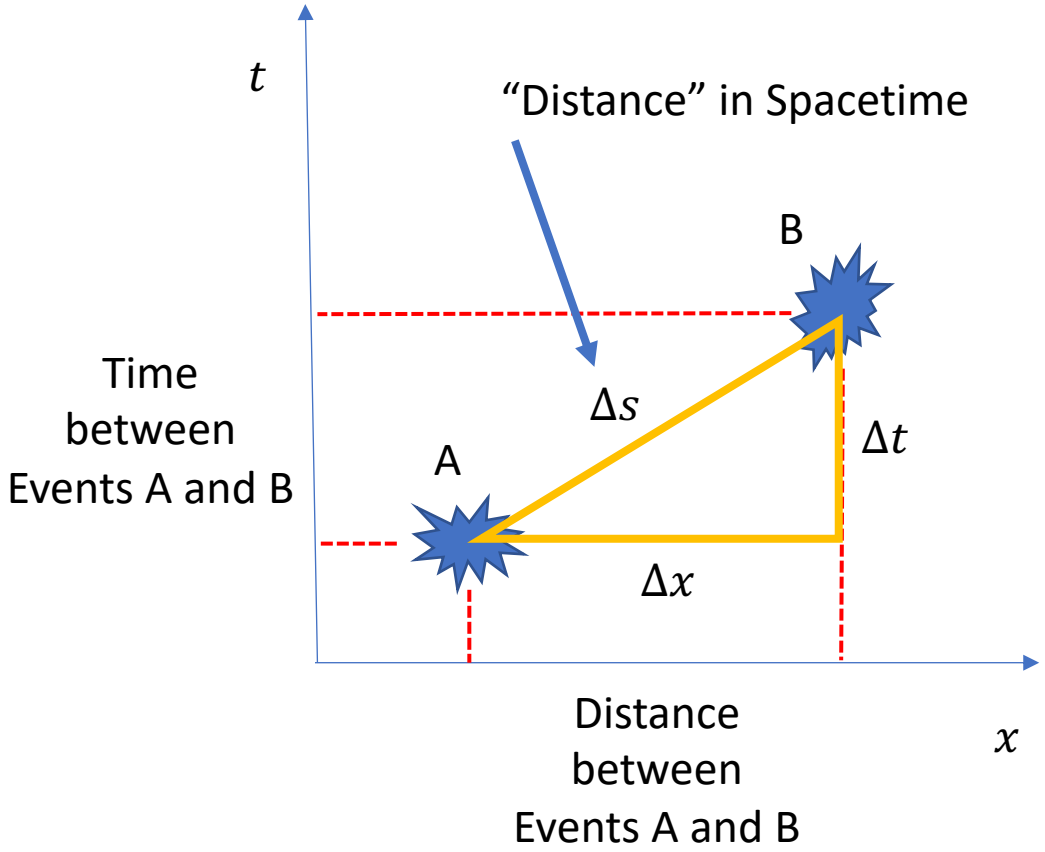


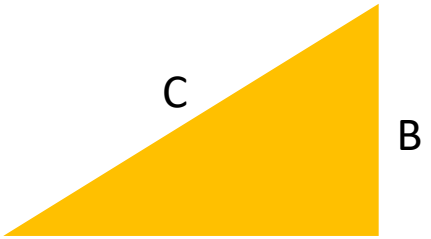
Because of Postulate 2, the spheres expand in the same way in both reference frames.

Space

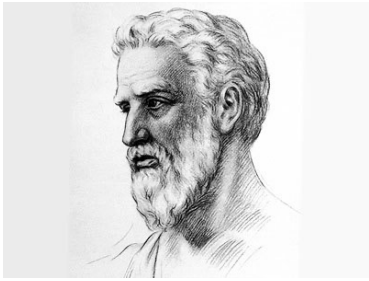


Space+Time=Spacetime



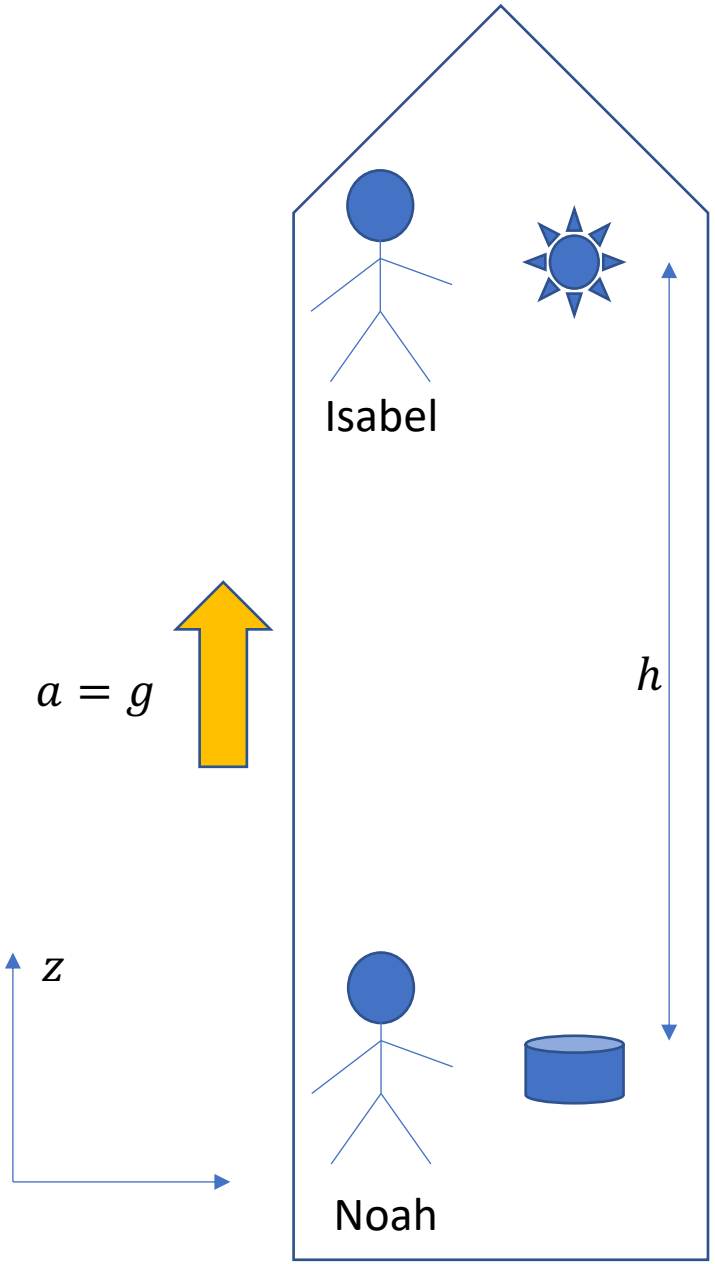


$A^2 + B^2 = C^2$



$$(\Delta s)^2 = -(c\Delta t)^2 + (\Delta x)^2$$

Time in an Accelerated Reference Frame



Isabel sends out a flash of light at regular intervals: Δt_I

Noah receives a flash of light at regular intervals: Δt_N

$$z_{Isabel} = h + \frac{1}{2}gt^2$$

$$z_{Isabel}(0) - z_{Noah}(t_{first\ detection}) = ct_{first\ detection}$$

$$z_{Isabel}(\Delta t_I) - z_{Noah}\left(t_{first\ detection} + \Delta t_N\right) = c\left(t_{first\ detection} + \Delta t_N - \Delta t_I\right)$$

$$\Delta t_N = \left(1 - \frac{gh}{c^2}\right)\Delta t_I$$

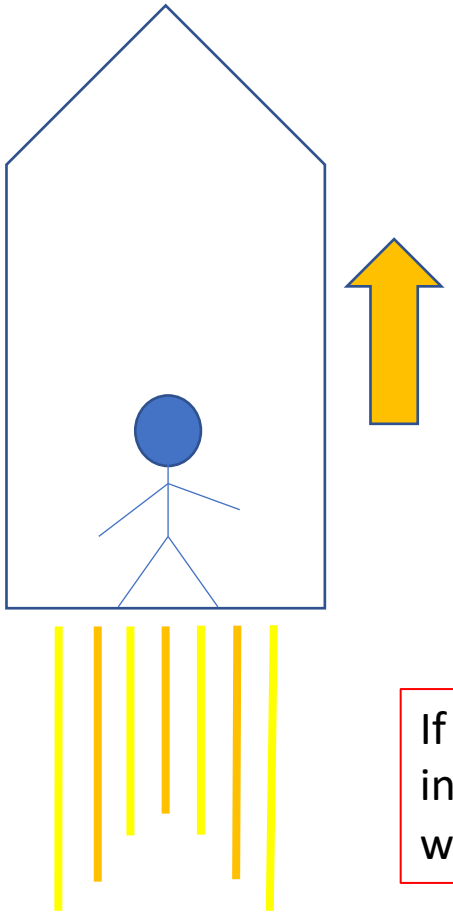
$$\Delta t_I > \Delta t_N$$

$$z_{Noah} = \frac{1}{2}gt^2$$

Time between events – in this case the time between light pulses – is shorter for Noah.

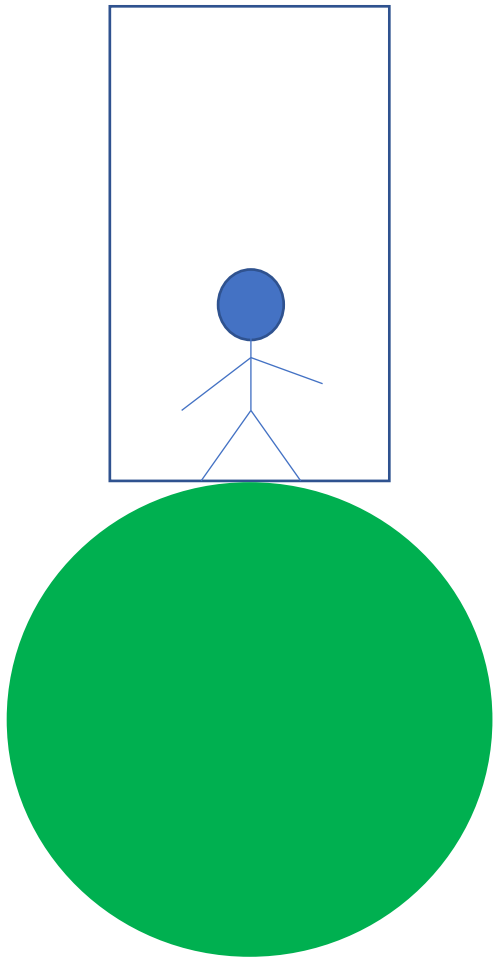
➡ Time is passing more slowly for Noah.

Indistinguishable Experiments

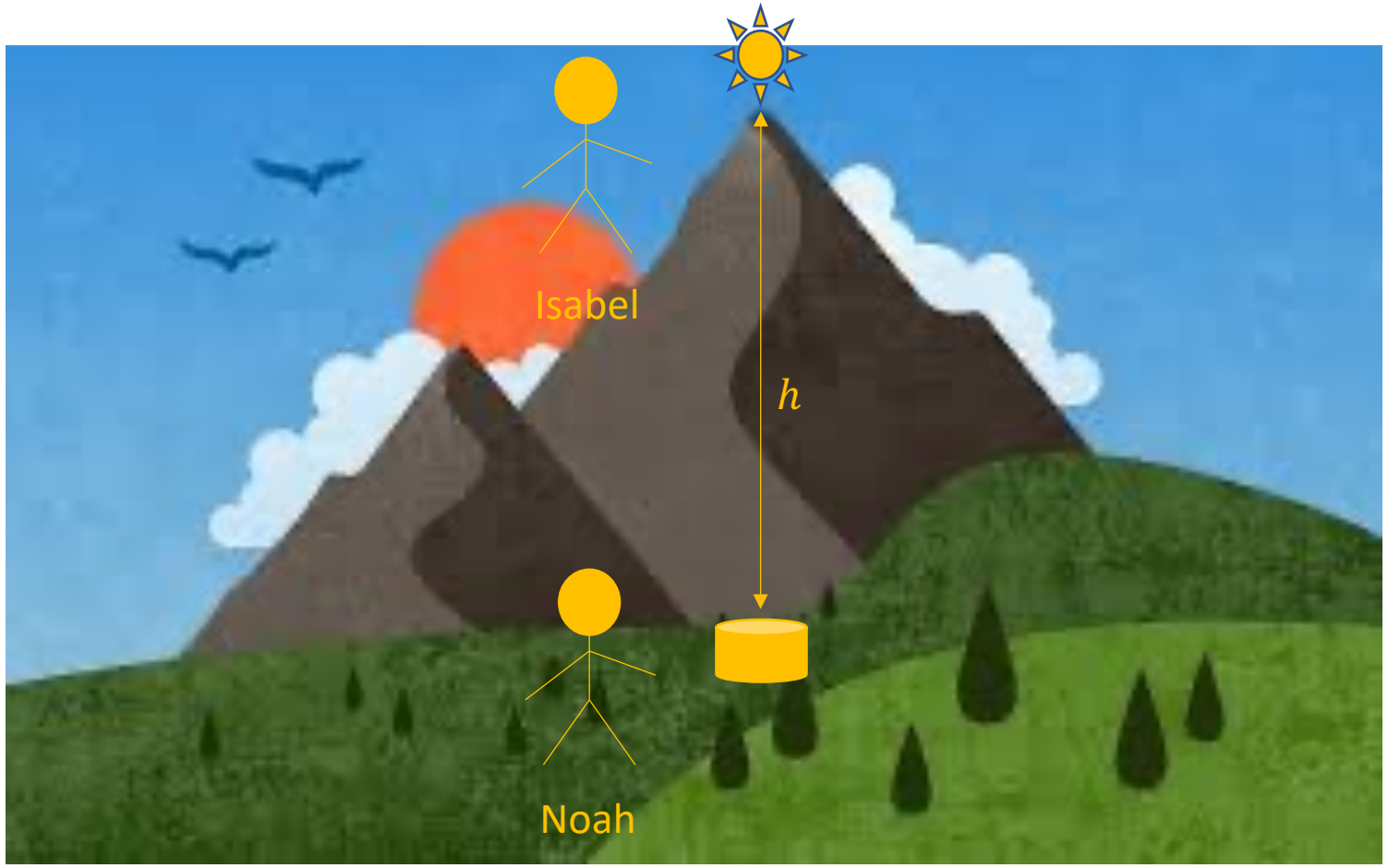


$a = g$

If our observer releases a ball initially at rest, in both cases what happens?



Time in Gravitational Field

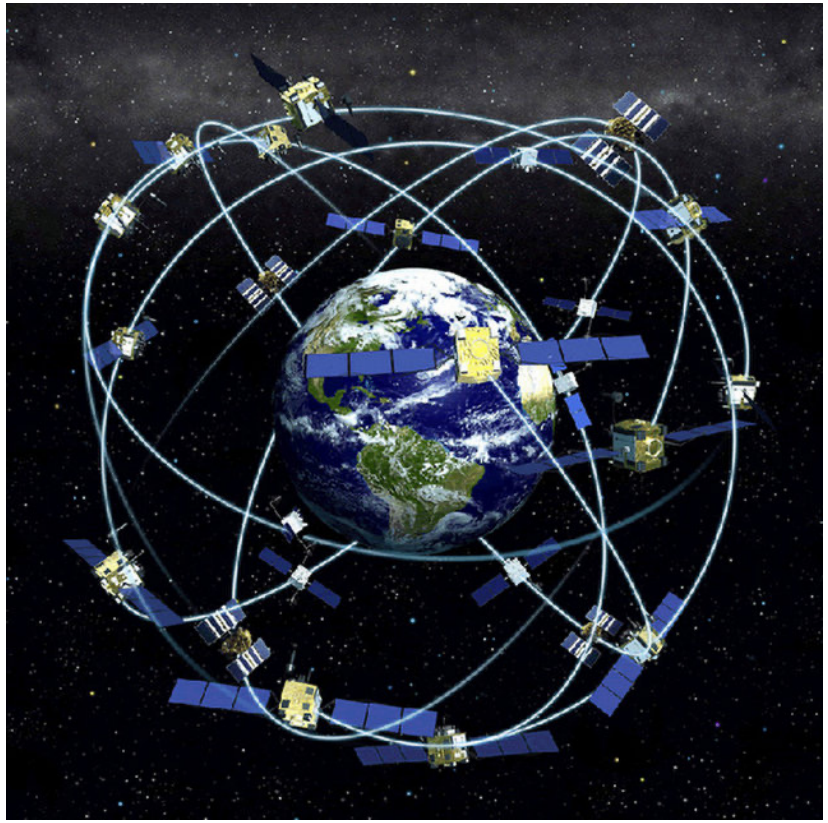


$$\Delta t_N = \left(1 - \frac{gh}{c^2}\right)\Delta t_I$$

Interstellar

$$\frac{\Delta t_I - \Delta t_N}{\Delta t_I} = 1\times10^{-15}$$

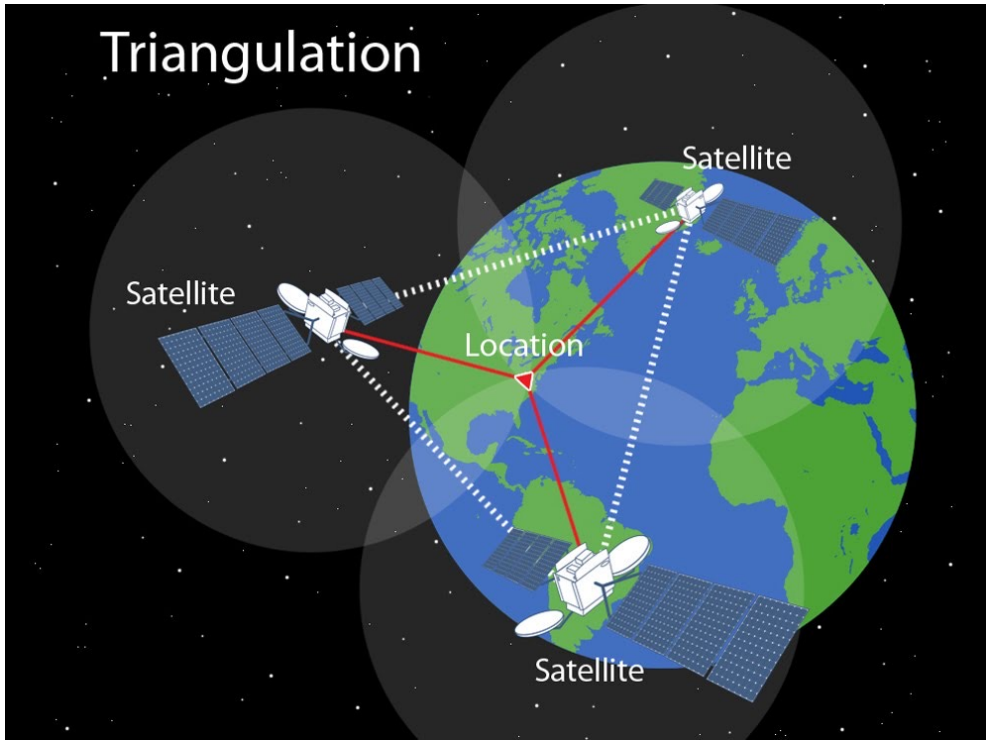
Difference in time between the top of Mount Everest and sea level: one quadrillionth of a second per second.



GPS Satellite System
24 satellites in 12-h orbits in 6 orbital planes

GPS

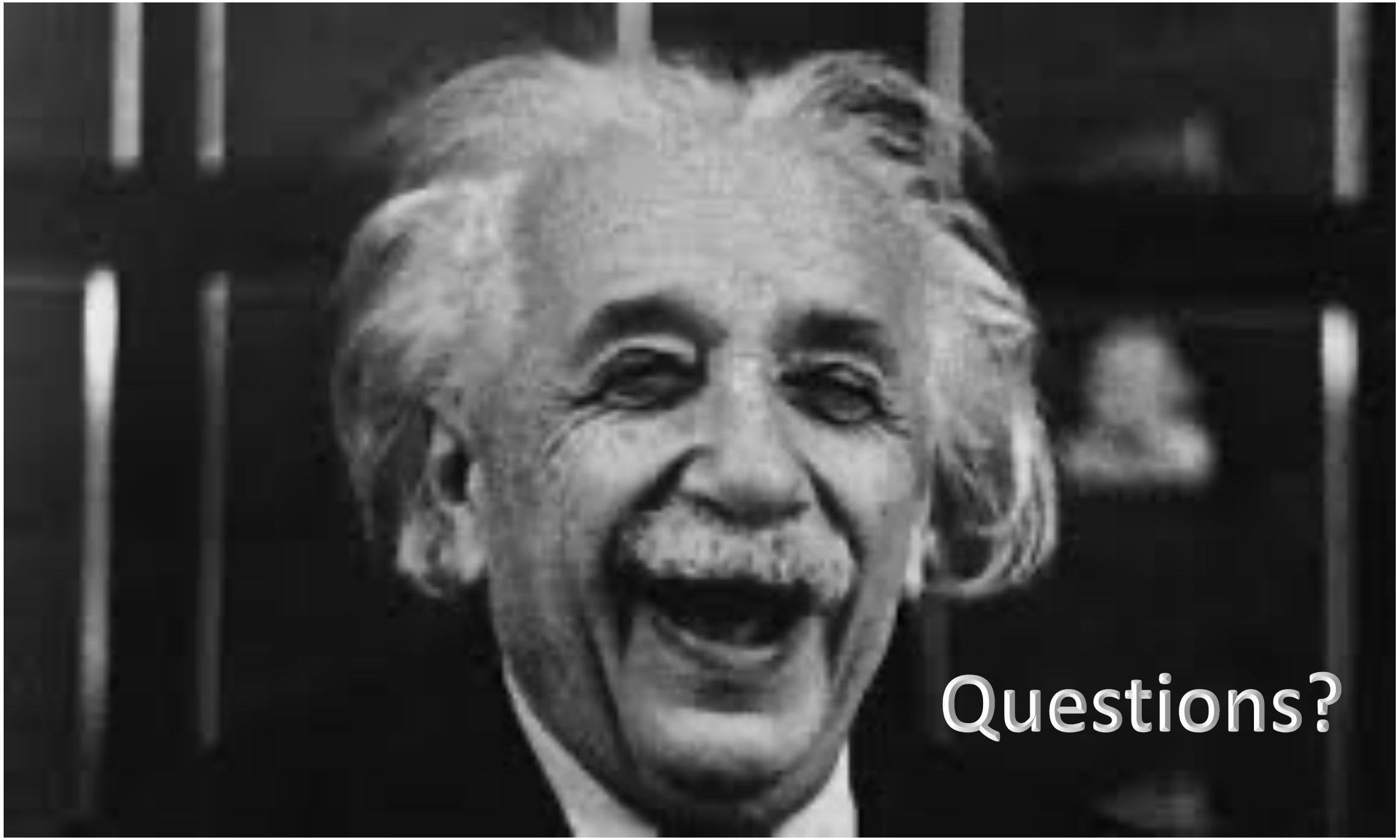
- 1 satellite locates you anywhere on a sphere
- 2 satellites locate you anywhere on a circle
- 3 satellites locate you at one of two points
- 4 satellites locate you at a single point



<u>But:</u>

- *satellite motion: time passes more slowly at the satellite relative to Earth – 5 ns ahead on Earth in 1 min*
- *gravity: time passes more quickly at the satellite relative to Earth – 25 ns behind on Earth in 1 min*

☞ *Distance Error on Earth: ~ ¼ mile in an hour*


Questions?