C.L. Poor [Physics Dept., Columbia Univ.] on Relativity (1919)

"Social unrest and creeping Bolshevism [have] invaded science, leading people to 'throw aside the well-tested theories upon which have been built the entire structure of modern science and mechanical development in favor of psychological speculations and fantastic dreams about the universe'."

From Jeffrey Crelinsten, **Einstein's Jury** (Princeton, 2006), p. 151.

1

About the Final Exam

- Covers the entire course
  - Emphasis on material since the test
  - Classes, Practicals, MasteringPhysics
- 11 Multiple Choice questions
- Three "Long Answer" Problems
  - One is fairly short
- Same format as the test
  - Closed book
  - A non-programmable calculator
  - Single 8 ½ x 11 inch sheet of paper on which you may write anything that you wish on both sides
- We will supply all required constants

2

Reminders

- The On-Line Help Centre will be available
  - Check the hours on the portal
- Prof Strong has posted a review of Electricity & Magnetism on the portal

3

Last Time

- Addition of Velocities $u_{Sue} = \dfrac{u_{Lou} - v}{1 - u_{Lou} v / c^2}$
- Momentum $\vec{p} = \dfrac{1}{\sqrt{1 - u^2/c^2}} m\vec{u}$
- Energy $E = \dfrac{1}{\sqrt{1 - u^2/c^2}} mc^2$
  - Rest energy $E_o = mc^2$
  - Mass-energy equivalence
  - Pair production & annihilation

4

Today

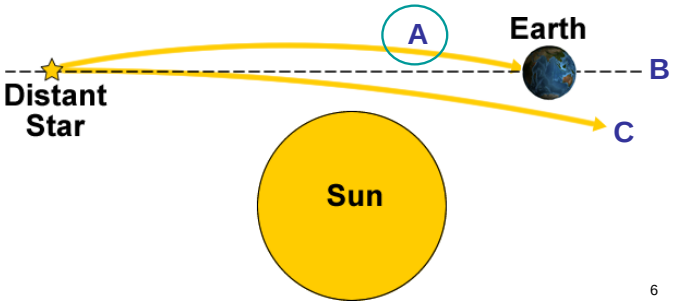
- The General Theory of Relativity (1916)
  - Three pieces used by Einstein in building the theory
    1. Geometry is Physics (Riemann)
    2. Inertia *here* is due to mass *there* (Mach)
    3. Acceleration is equivalent to gravitation (Einstein)

5

A Distant Star, the Sun and the Earth

Two light rays from the star are shown.

Which best defines a “straight line” from the Star to the Earth?



6

Geometry is Physics

"So long as one believes that the universe is a big machine, it is natural to think that its various parts can exert a force on one another. But the deeper science probes toward reality, the more clearly it appears that the universe is not like a machine at all. So Einstein's Law of Gravitation contains nothing about force. It describes the behavior of objects in a gravitational field - the planets, for example - not in terms of `attraction' but simply in terms of the paths they follow.“

Lincoln Barnett, **The Universe and Dr. Einstein**, pg. 42

7

Experimental Measurements of the Difference Between Inertial and Gravitational Mass

- Galileo (1590?): < one part in 200
- Newton (1686): < one part in a 1000
- Eotvos (1922): < one part in 4×10^9
- Baeßler et al. (1999): < one part in 5×10^{12}

Coming (STEP, 2013?): a satellite-borne instrument with a sensitivity ~ one part in 10^{18}

8

The Earth Rotates On Its Axis

So when we stand on Earth, we are actually moving in a circle with a period of 24 hours.

Are we really in an *inertial reference frame*?

A. Yes
B. No

9

Foucault Pendulum

10

Ernst Mach on the Foucault Pendulum

"The universe is not *twice* given, with an earth at rest and an earth in motion; but only once, with its *relative* motions alone determinable. It is accordingly, not permitted us to say how things would be if the earth did not rotate."

11

Mach's Principle

Imagine a test mass in a universe with no other matter in it. Will conservation of momentum be true for the test mass?

A. Yes
B. No

But the universe is not twice given!

12

You are in the TARDIS (a small booth in *Dr. Who*)
You can not look out the windows
Assume the Earth is a good inertial frame

Either the TARDIS is stationary on Earth or is in free space and accelerating up at 9.8 m/s^2 relative to the Earth. Can you do an experiment to determine which is the case?

A. Yes

B. No

13

Two falling balls

14

You are in the TARDIS (a small booth in *Dr. Who*)
You can not look out the windows
Assume the Earth is a good inertial frame

Either the TARDIS is in free space far from Earth and stationary relative to it, or it is in free free fall near the Earth's surface. Can you do an experiment to determine which is the case?

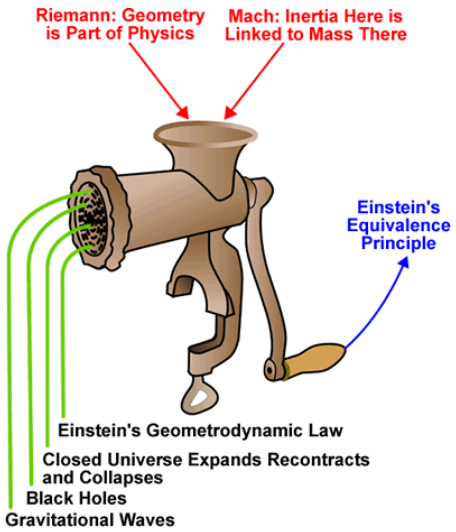
A. Yes

B. No

15

"For an observer in free fall off the roof of his house, there exists for him during his fall no gravity." -- Einstein

16



17

Einstein in 1912

"I am exclusively occupied with the problem of gravitation and hope with the help of a local mathematician friend [Marcel Grossman] to overcome all the difficulties. One thing is certain, however, that never in life have I been quite so tormented."

18