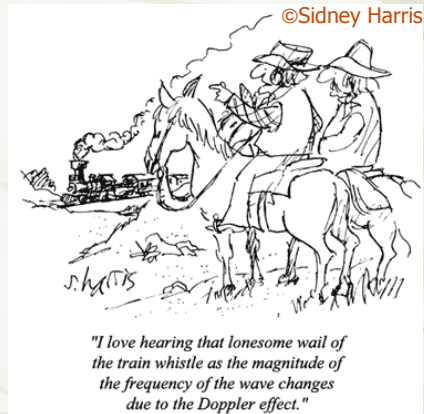


Lecture 11: General Relativity I

- ★ Einstein Tower Experiment
- ★ Gravitational redshifting
- ★ Strong Equivalence Principal

10/7/10



1

0: RECAP OF SPECIAL RELATIVITY

- ★ Einstein's postulates
 - ★ Laws of physics look the same in any inertial frame of reference.
 - ★ The speed of light is the same in any inertial frame of reference
- ★ Strange consequences
 - ★ Time dilation and length contraction
 - ★ Relativity of simultaneity and ordering of events
 - ★ Equivalence and conversion of mass and energy
- ★ Why have we been so carefully avoiding gravity until now?

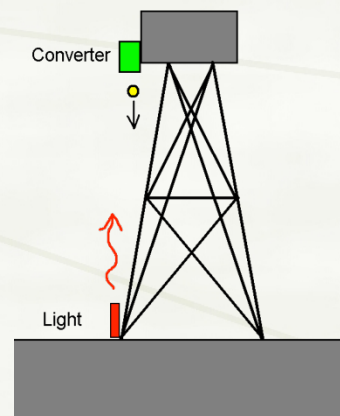
- ★ Discussion: Suppose we simply supplement the Special Theory of Relativity with Newton's law of gravity... what things go wrong?

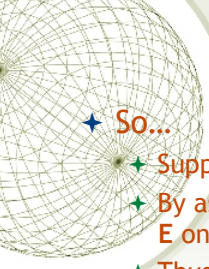
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3

I: EINSTEIN'S TOWER

- ★ Another thought experiment... suppose that light is not affected by gravity.
- ★ Consider a tower on Earth
 - ★ Shine a light ray from bottom to top
 - ★ When light gets to top, turn its energy into mass.
 - ★ Then drop mass to bottom of tower.
 - ★ Then turn it back into energy



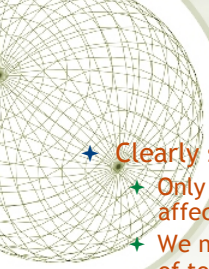


★ So...

- ★ Suppose original photon energy E
- ★ By assumption, it is not affected by gravity so it has energy E once it reaches top
- ★ Thus, mass created at top is $m=E/c^2$
- ★ Then drop mass... at bottom of tower, it has picked up speed due to the conversion of gravitational potential energy ($E_{\text{grav}}=mgh$)
- ★ When we convert it back into energy, we have

$$E_{\text{new}} = E + mgh = E \left(1 + \frac{gh}{c^2} \right)$$

- ★ We have made energy! We're rich!!!!



★ Clearly something is wrong with our assumptions...

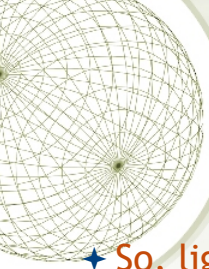
- ★ Only way we can conserve energy is to suppose that light is affected by gravity...
- ★ We need the photon to lose energy as it climbs upwards... at top of tower, we must have

$$E_{\text{top}} = E \left(1 + \frac{gh}{c^2} \right)^{-1}$$

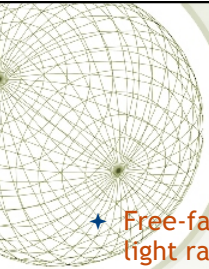
- ★ This is known as **gravitational redshift**

★ The profound nature of gravitational redshift...

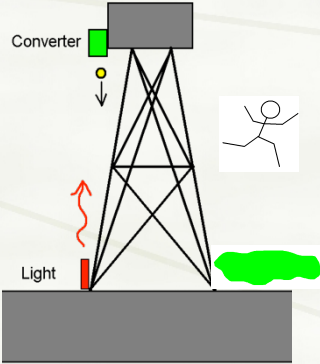
- ★ Imagine a clock based on the frequency of light
- ★ Place the clock at the base of the tower... observe it from the top.
- ★ Photons lose energy... so they decrease frequency
- ★ Thus, we see the clock running slowly!
- ★ **Time passes at a slower rate in a gravitational field!**



- ✦ So, light is affected by gravity...
 - ✦ But gravity does not appear in Maxwell's equations
 - ✦ Thus, Maxwell's equations are not valid in the reference frame of Earth's surface.
 - ✦ The Earth's surface must not be an inertial frame of reference.



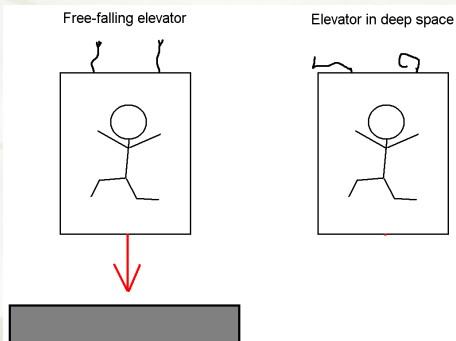
- ✦ Free-falling (FF) observer sees light ray travel unaffected by gravity.
- ✦ From "Earth's" frame...
 - ✦ Free-falling (FF) observer traveling faster and faster
 - ✦ FF observer would see an increasing *blueshift*
 - ✦ Since FF observer sees an unaffected (i.e. constant frequency) light beam, light must get progressively *redshifted* as it climbs up.
 - ✦ Redshifting removes just the right amount of energy to solve tower paradox.



II: STRONG EQUIVALENCE PRINCIPLE

- ★ Recap of the **weak equivalence principle**
 - ✦ All objects accelerate at the same rate in a given gravitational field.
 - ✦ In other words, inertial and gravitational masses are the same for any object.
- ★ Einstein introduced the **strong equivalence principle** - when gravity is present, the inertial frames of Special Relativity should be identified with free-falling frames of reference.
- ★ What does this mean???

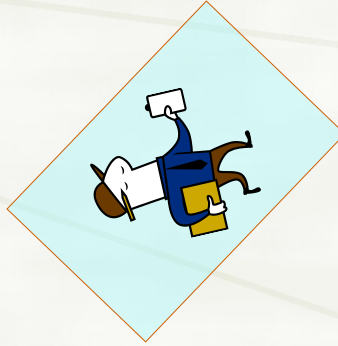
- ★ There is **no way** of telling the difference between a free-falling frame in a gravitational field and an inertial frame in no gravitational field... the two are equivalent.



Interior of elevator free-falling on Earth is equivalent to interior of elevator floating freely in deep space



$a=9.8 \text{ m/s}^2$



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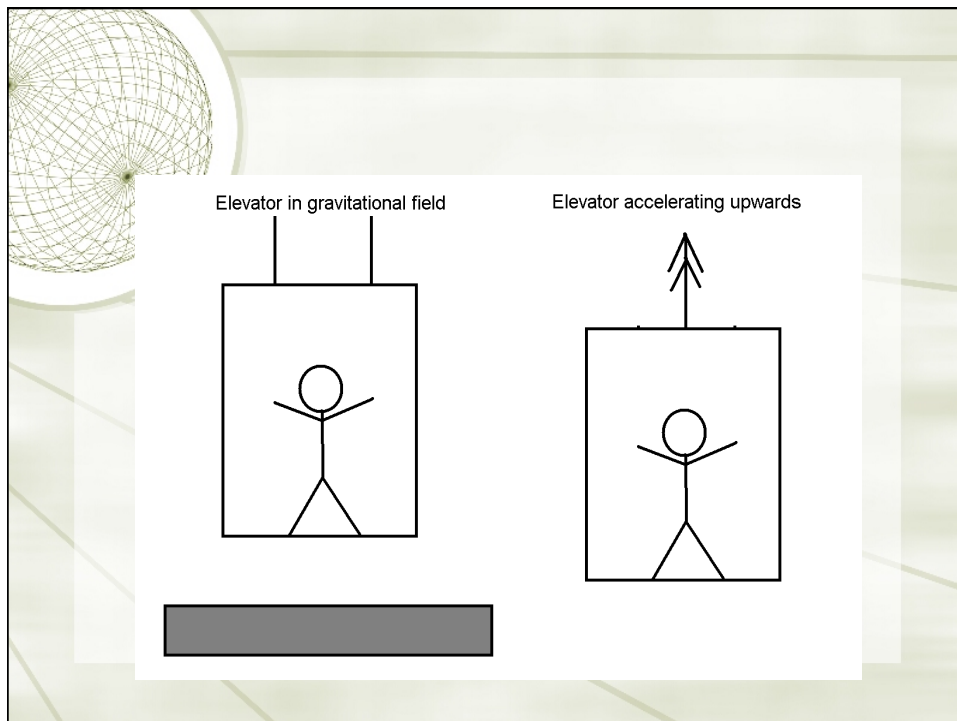
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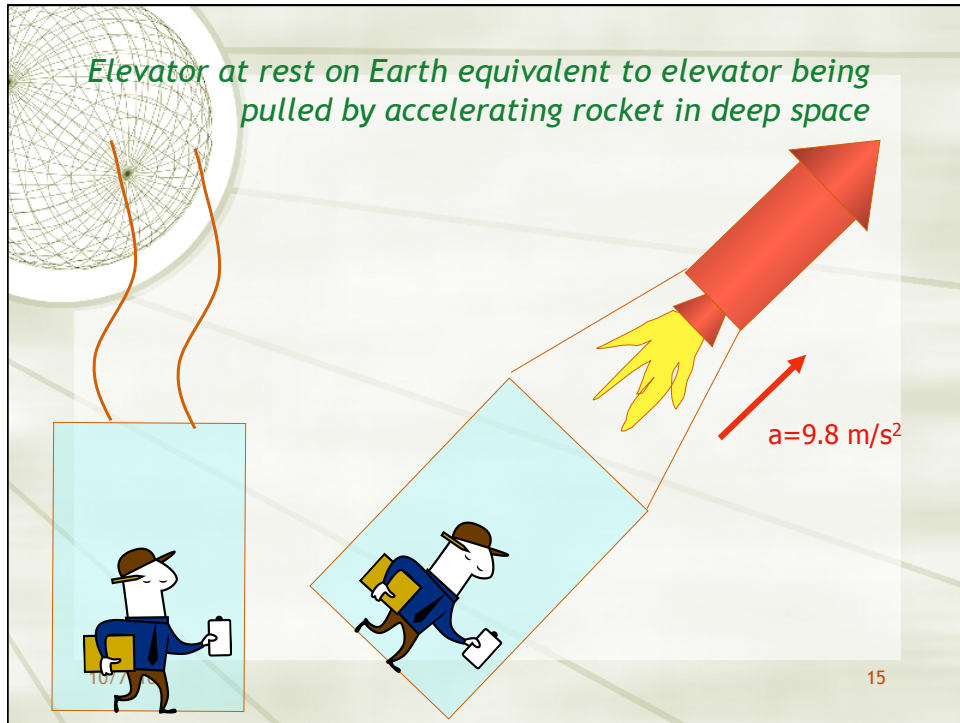
Back to the Astronauts...



What about gravity?

- ✦ Suppose that you decide that your frame of reference is not inertial...
 - ✦ Freely moving bodies change velocity
 - ✦ Is it because of gravity or is the frame accelerating?
 - ✦ Einstein says that you cannot tell the difference!
 - ✦ Gravity is a “fictitious force” - i.e., a force which appears to exist because we are living in a non-inertial frame of reference.





Light falls!

- ✦ Astronaut in inertial frame with flash light
 - ✦ Inertial frame, so light goes in straight lines
- ✦ What if we now look at the same light path from an accelerating reference frame?
 - ✦ Light beam will bend - it appears to fall
 - ✦ Important conclusion - light "falls" due to gravity!

Inertial Frame

Accelerating frame or gravity



The Eddington Test

- ★ 1919 - the first “accessible” total Solar eclipse since Einstein postulated SEP
- ★ Arthur Eddington
 - ★ Famous British Astronomer
 - ★ Lead expedition to South America to observe eclipse
 - ★ Was looking for effects of gravitational light bending by searching for shifts in positions of stars just next to the Sun.
 - ★ He found them, exactly as predicted!



Giant lenses in the sky

