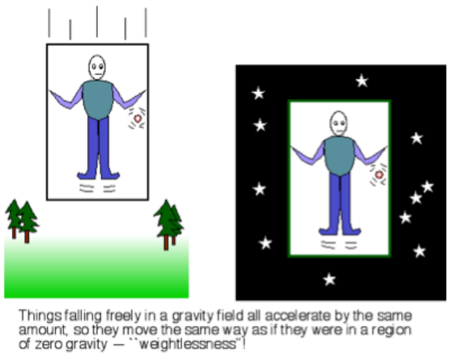
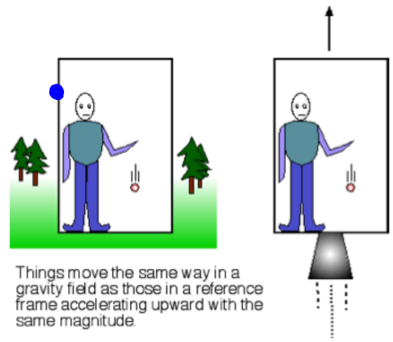
Einstein's Principle of Equivalence:

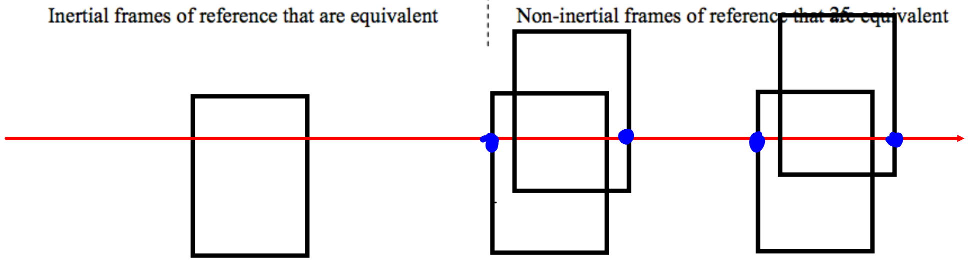
A frame of reference accelerating in empty space is equivalent to a frame of reference at rest in a gravitational field





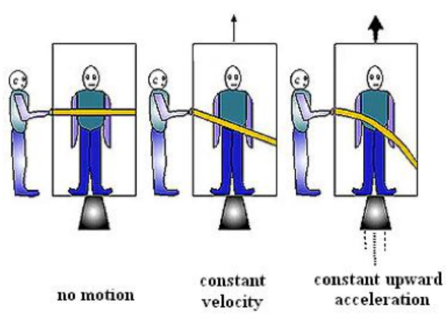
Inertial frames of reference that are equivalent

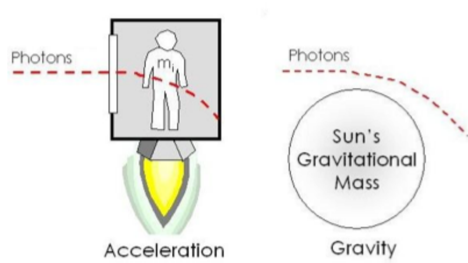
Non-inertial frames of reference that are equivalent



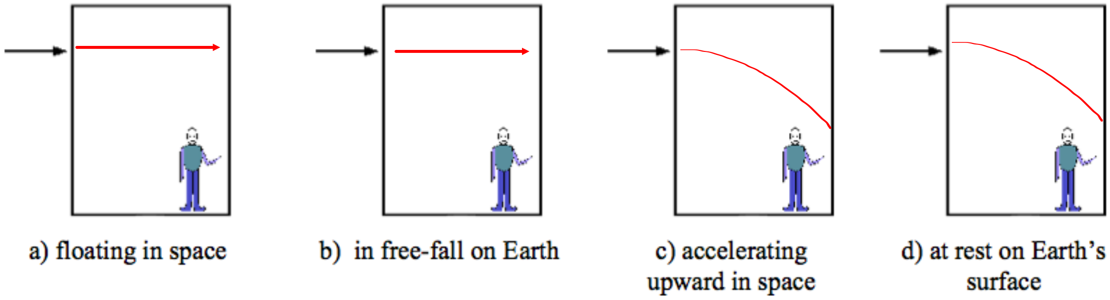
Based on the principle of equivalence, Einstein predicted that . . .

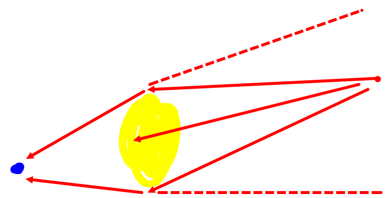
light rays will bend in gravitational fields. (gravity bends light)





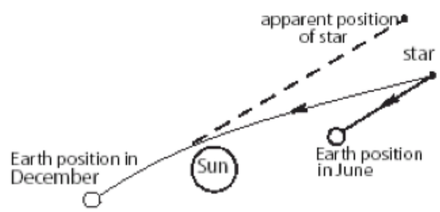
Sketch the path of the light beam across each elevator.





Eddington's solar eclipse measurements

The positions of several stars were measured against a background of fixed stars. Six months later, those stars were hidden behind the Sun due to Earth's new position in its yearly revolution. It was predicted by General Relativity that these stars should still be visible if the gravitational field of the Sun bent the light rays around it and deflected the light rays toward Earth. However, these "hidden" stars would still not be visible due to the glare of the Sun.

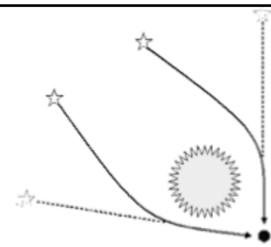


But an expedition led by Sir Arthur Eddington sent to the island of Principe sought to measure the deflection of these light rays during a total eclipse of the Sun in 1919 when the stars would be briefly visible. He measured the new positions of the stars against the background of fixed stars and found that they had apparently shifted position.

Importance:

Experimental evidence for the bending of light by a gravitational field

Gravitational lensing: Massive galaxies can deflect the light from distant sources of light so that the rays bend around the galaxy. The galaxy acts like a lens so that observers on Earth can see multiple images of the source.



Importance:

Experimental evidence for the bending of light by a gravitational field

Based on the principle of equivalence, Einstein predicted that . . . .

time slows down near a massive body. (gravity slows time)

Clocks near the surface of the Earth . . .

run more slowly than clocks at higher altitudes

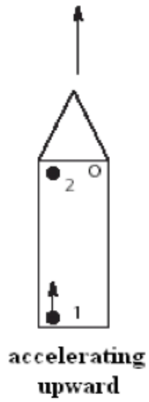
Gravitational Red Shift: the increase in wavelength (or decrease in frequency) of light when it moves from a stronger to a weaker gravitational field

Explanation: The frequency of vibration of an object or of an electromagnetic wave (a photon) is essentially a measurement of time. Slowing the frequency of vibration means that time is running slower. The decrease in frequency of vibration in a gravitational field can be explained in two different ways.

$E = h\nu$

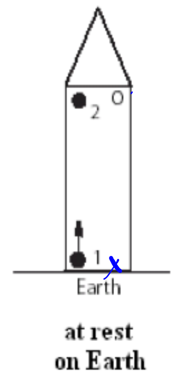
Doppler Shift

Consider a rocket with a light source at the bottom (1) and a detector at the top (2), as shown in (a). If the rocket accelerates upward, the detector will be accelerating away from the light source. Thus, the light waves from 1 will reach the detector at 2 less frequently, hence the received frequency will now be less than the emitted frequency, that is, the frequency will be shifted to a lower (redder) frequency.



Energy Loss

Consider a rocket at rest on the surface of Earth. As a photon moves from the bottom (1) to the top (2), it gains potential energy due to the gravitational field. Since its total energy must remain constant, it will lose "kinetic" energy. Since the energy of a photon is $E_{photon} = hf$ this means that its frequency will decrease.



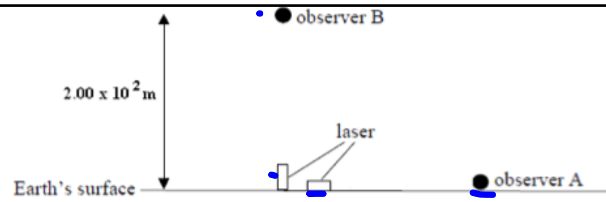
Result: Since a lower frequency means a higher period, in both cases it will appear to an observer at the top that clocks at the bottom are running slower.

Gravitational Red-Shift Frequency Formula:

$$\frac{\Delta f}{f} = \frac{g}{c^2} \Delta h$$

Assumption: g is constant

1. Two identical lasers are at rest on the Earth's surface, each pointed towards a different observer. Observer A measures the frequency of the laser to be 6.89 x 10^{14} Hz.



a) Does observer B measure a frequency that is greater, less or the same as that measured by observer A?

lower

b) Calculate the difference in frequencies as measured by the two observers.

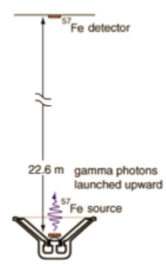
15hz

c) If this experiment was repeated in a rocket ship in space far from any massive bodies, how fast would the rocket have to accelerate for the results to be the same? Justify your answer.

9.8

Evidence to support gravitational red-shift effect

1. **Experiment**: Pound-Rebka experiment



In the early 60's physicists Pound, Rebka,and Snyder at the Jefferson Physical Laboratory at Harvard measured the shift in gamma rays emitted from iron-57 by placing a source at the base of Harvard Tower and a detector at its top, a distance of 22.6 m higher. They were able to measure the shift in frequency of the photons and the results agreed with the predicted value to within 1%.

2. **Experiment**: Shapiro time delay experiment

The delay in time taken for a radar pulse to travel to a nearby planet (Venus or Mercury) and return due to gravitational field of the Sun was measured in 1960s. Results agreed with general relativity predictions.