Gravity

By the end of this chapter, you will be able to:

- Know and differentiate the four fundamental forces
- Use proportions to understand how the force of gravity changes as masses and distance between objects changes
- Solve problems with the Law of Universal Gravitation
- Describe orbits
- Describe the tidal force
- Describe how scientists currently think of gravity
- Describe a black hole

Forces

- Fundamental Forces
  - There are four fundamental forces in the universe
    - They are fundamental in that they are the most basic
    - Everything force that you see/experience is a manifestation of one of these four
  - Gravity
    - Acts as an attractive force between objects with mass
    - Gravity is by far the weakest force
    - It also acts over the farthest distances

- Electromagnetic Force
  - Acts as an attractive or repulsive force between electric charges
    - Positive and negative charges
  - The force that acts over the second longest distances
  - Other than gravity, almost every force you encounter during your daily life is a variation of the electromagnetic force
- Weak Nuclear Force
  - Governs nuclear decay and other nuclear reactions
  - Does not act outside the nucleus of the atom
  - Scientists know that at one point in time, early in the universe, the electromagnetic and the weak nuclear force were the same thing
    - Called the Electroweak Force

- Strong Nuclear Force
  - Holds the nucleus together
  - Acts between protons and neutrons in the nucleus of the atom
  - Does not act outside the nucleus of the atom

- Sir Isaac Newton (1642 - 1727)
  - English physicist, mathematician, astronomer, natural philosopher and alchemist
  - Reportedly developed his law of universal gravitation by watching an apple fall from a tree
    - This is his own story and unlikely to be true
  - He developed Calculus to solve his physics problem
    - He was attempting to come up with a mathematical way to describe the force that would keep planets in an elliptical orbit
    - This ended up being his law of universal gravitation

– Law of Universal Gravitation

- It is called the universal law because the law describes how gravity acts throughout the universe
- At the time this was a bold claim, that one man could figure out how the universe moved

$$F_{Gravity} \propto \frac{m_1 m_2}{r^2}$$

- Manipulating the Law of Universal Gravitation

$$F_{Gravity} \propto \frac{m_1 m_2}{r^2}$$

Force is proportional to the product of the masses and inversely proportional to the square of the distance between the objects.

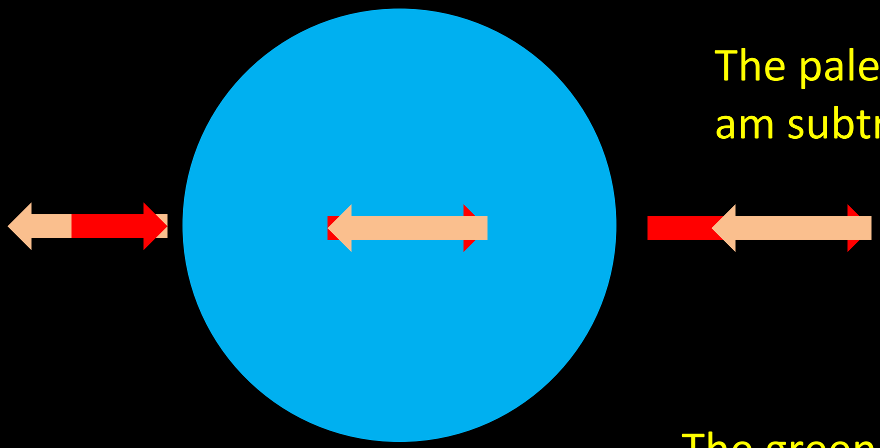
  - What happens to the force if you double one of the masses?
    - You double the force between the objects
  - What happens to the force if you double both masses?
    - You increase the force by a factor of four
  - What happens to the force if you triple one mass and decrease the other by a factor of 4?
    - You will decrease the force by a factor of 3/4

- What happens to the force if you double the distance between the objects?
  - The force decreases by a factor of 4
- What happens to the force if you triple the distance between the objects?
  - The force decreases by a factor of 9
- What happens to the force if you decrease the distance by a factor of 2?
  - The force increases by a factor of 4
- What happens to the force if you decrease the distance by a factor of 5 and increase both masses by a factor of 8?
  - The force will change to 1600x its previous value

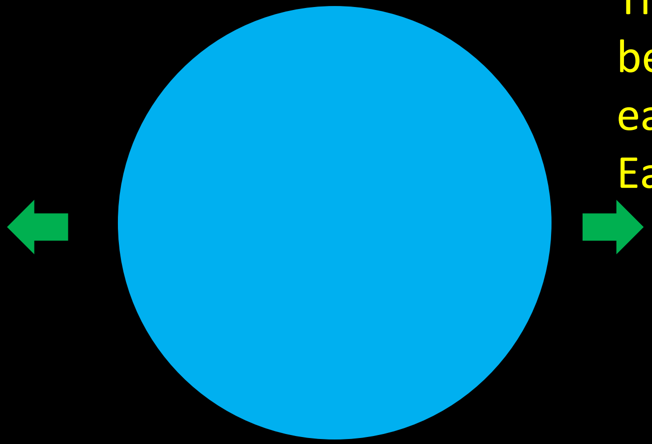
- Orbits
  - The curvature of the Earth
    - The surface of the Earth drops 5 meters vertically for every 8 km horizontally
  - In order to orbit the Earth, you need to travel 8 km in the time it takes you to fall 5 m
    - It turns out that the time it takes to drop 5 m is about 1 s
  - Therefore, orbital velocity of Earth is 8 km/s
    - Meaning that if you are able to get an object in space moving at 8 km/s, it will fall around the Earth forever
      - In other words, it will orbit
  - To escape Earth's vicinity, you need a horizontal velocity of at least 11.2 km/s

- Tidal Force
  - The tidal force is a secondary effect of gravity
    - It arises because the pull of gravity from one object to another is not even across the surface, from the near side to the far side
      - Example:
        - » The pull of gravity on the Earth from the Moon is not even
        - » The Moon's gravity pulls on the near side of the Earth harder than it pulls on the far side of the Earth

- The tidal force is a differential force
  - It is due to the DIFFERENCE of the force from one side to another
  - So, I am going to subtract F_g on the center of the Earth from the pull of gravity from the Moon
  - This will show the effect of the difference between the sides of the Earth without the effect of Moon's gravity at the center

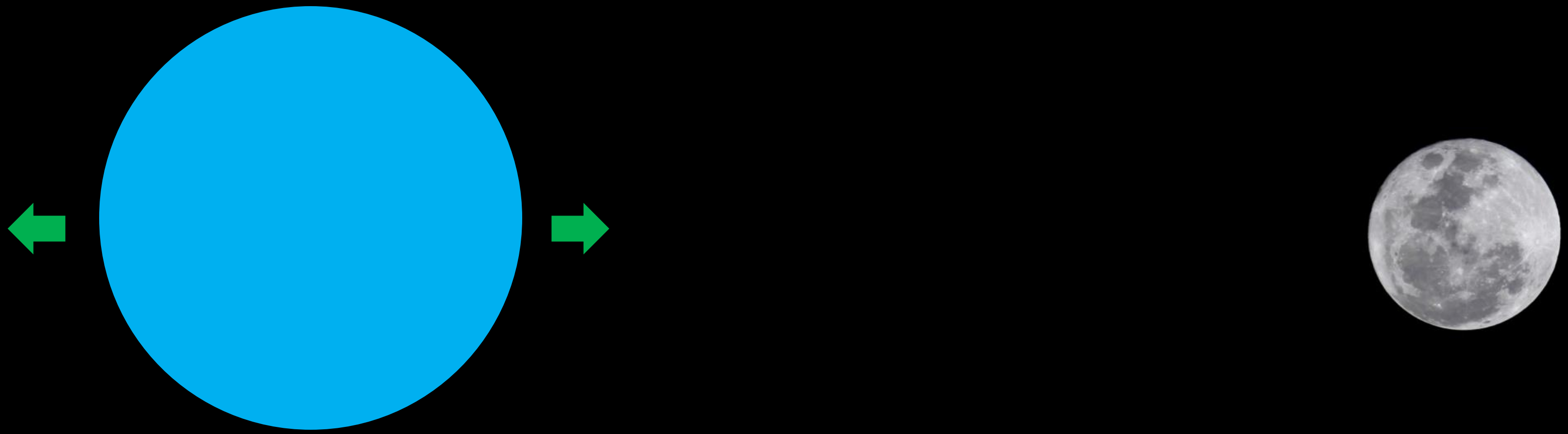


The pale arrow is the F_g that I am subtracting off



The green arrows represent the difference between the pull of the Moon's gravity on each side and the pull on the center of the Earth

- The green arrow is the tidal force
  - As you can see, the tidal force pulls the side of the Earth closest to the Moon towards the Moon
  - It ALSO pushes the side of the Earth that is farthest away from the Moon away from the Moon



  - This is why there are TWO high tides a day, instead of the one that you would expect
    - » The water builds up both under the Moon and on the opposite side of the Moon

- Universal Gravity Equation
  - While the ability to predict how the force of gravity will change based on a change in mass or distance is nice, it would be much more preferable to be able to calculate the force of gravity from masses and the distance
    - To be able to turn the above proportion to an equation we need a proportionality constant
    - This proportionality constant is called “G”
  - This proportionality constant was unknown to Newton
    - It was first measured in 1798 by a scientist named Henry Cavendish

- From his experiments, he was able to measure the value of "G" to be the following:

$$G = 6.67x10^{-11}\frac{N \cdot m^2}{kg^2}$$

- This means that the law of universal gravity (the proportion) can be turned into the following equation

$$F_{Gravity} = G\frac{m_1 m_2}{r^2}$$

- Weight
  - By definition, weight is the force of gravity acting on an object

$$F_{Gravity} = G\frac{m_1 m_2}{r^2} = W = mg$$

  - From this definition, the acceleration due to gravity can be calculated for any object
    - In the following example, let's calculate the acceleration due to gravity of Earth

Start with the equation for the weight and the universal gravity equation

$$mg = G\frac{m_1 m_2}{r^2}$$

Since we are looking at the gravitational attraction between an object and Earth, we can substitute values for the mass of Earth and the radius of Earth

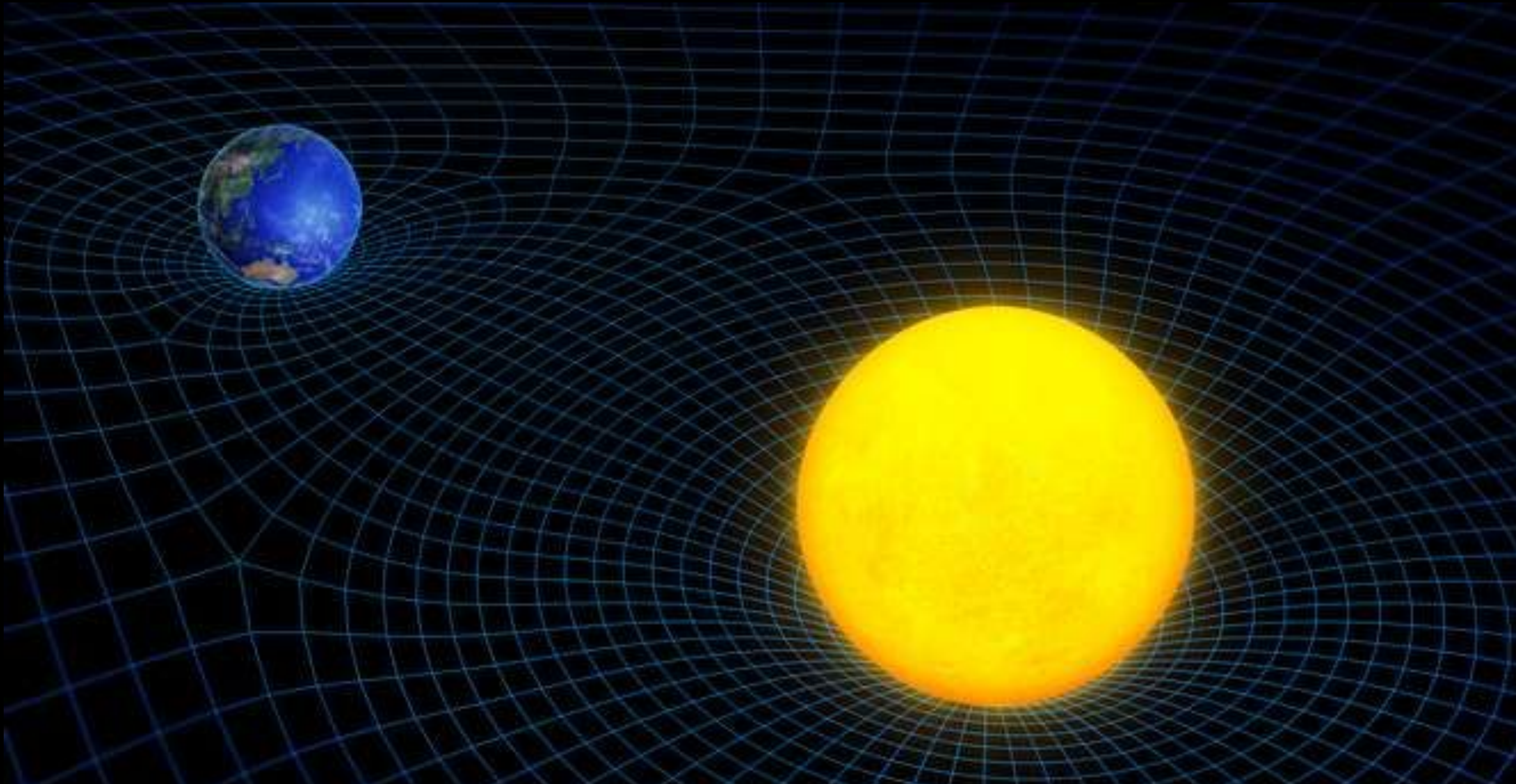
$$mg = G\frac{m_1 m_E}{r_E^{\,2}}$$

Since the mass of the object appears on both sides, cancel to give you a mathematical calculation for “g”

$$g = G\frac{m_E}{r_E^{\,2}}$$

- Theory of General Relativity
  - Albert Einstein published a paper on the Theory of General Relativity in 1915
    - In it, he proposed that gravity is not a force but an effect of space itself
    - The fabric of space-time gets bent and curved in the presence of mass
      - The more mass an object has, the more it curves and bends space
      - Earth, being about 100 times more massive than the Moon, curves space more than the Moon

Astrophysicist Brian Greene explaining General Relativity



Visualization of Earth and Sun and how they affect the curve of space-time

As you can see from the picture, the sun curves space-time more than the earth. General Relativity says that this occurs because the sun is more massive than the earth

Photo Credit: https://phys.org/news/2015-11-einstein-theory-relativity-common-sense-physics.html

- Tests of General Relativity
  - To verify General Relativity, Einstein offered three tests
    - Precession of Mercury, measuring the deflection of starlight, gravitational redshift of light
    - There have been many more tests than just these three, even as late at 2016, but these are the ones we will go into detail on
  - Precession of Mercury
    - It was known all the way back in 1859 that Mercury's orbit did not behave as predicted by Newton's Law of Gravity
      - Mercury's orbit precesses, or rotates, over time
      - The observed amount of precession was larger than what Newton predicted
    - General Relativity made a prediction about Mercury's orbit that agreed with the data
    - It also predicted that all planets, and indeed all objects that orbit another, would have orbits that precess
      - Since then, the precession of Venus' and Earth's orbits have been measured and they agree with the prediction from General Relativity

- Deflection of Light
  - One of the consequences of General Relativity is that light should bend in the presence of a massive object
  - Light, as it travels, follows the curve of space-time
    - Therefore, if it travels near a massive object that is warping space the light should bend slightly
    - This was first measured on May 29, 1919 using a solar eclipse
    - Arthur Eddington and his teams set up to measure the apparent position of a group of stars called the Hyades
    - They then compared the measurements to the stars positions as measured at night
    - The difference in position of the star agreed with the prediction made using General Relativity

- Gravitational Redshift
  - In 1959, researchers at Harvard showed that electromagnetic waves traveling upward in a gravitational field lose energy
    - When talking about electromagnetic waves, this loss of energy decreases the frequency of the wave
    - This decrease is called a redshift since the frequency is moving towards the red end of the spectrum
  - The amount of energy lost was predicted by General Relativity
    - Another way to think about this is to say that clocks run slower the higher they are in a gravitational field
  - Today, this is probably the most well-tested part of General Relativity
    - GPS satellites must take this shift into account in order to operate
    - GPS satellites need their clocks adjusted by 38 μs everyday in order to operate
      - This is because GPS satellites operate using very precise atomic clocks
    - This time difference is because their clocks run slower since they are further away from Earth

- Black Holes
  - General Relativity predicts the existence of black holes
  - Black holes are massive objects in space with gravity so intense that light cannot escape
    - In other words, the escape velocity of the black hole is greater than 3.0×10^8 m/s
    - Since no light can escape, they have been dubbed “black”
    - However, just because we cannot see black holes does not mean that we cannot observe them
      - What we can observe are their effects on objects around them

– Observational Evidence of Black Holes

- A black holes defining characteristic is its immense gravitational pull
- Therefore a lot of our evidence for black holes is by observing objects that are orbiting black holes
  - In 1994, the Hubble Space Telescope, by observing the speed of a cloud of gas in galaxy M87, calculated the object at the center of the galaxy to have a mass of 3 x 10^9 times greater than our sun
    - The only object this could possibly be is a black hole
  - Since then, black holes have been observed in the center of many galaxies including our own
- Cygnus X-1
  - Cygnus X-1 is a binary system that contains a massive object that emits x-rays in bursts that last about ⅓ of a second
  - The visible star in binary system is a blue star
    - The problem is that blue stars do not emit x-rays unless there is another object syphoning off the gas from the star
    - Therefore, there must be another object in this system

- The second object was calculated to be very massive, at least 10 solar masses
  - It would have to be massive to pull the gas from the blue star
- The second object was also calculated to be very small, about a 160 km in diameter
  - The x-rays given off occur in bursts that are close together
  - The closer together the smaller the object that is syphoning the gas
  - This is because the source of the x-rays is the gas from the star falling into the second object
- The only object that we know of that fits these requirements is a black hole

Artist Depiction of the Cygnus X-1 system