Chapter 5

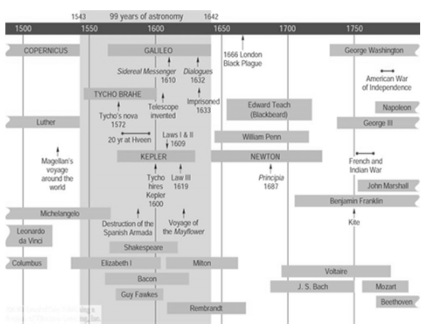
Gravity

Guidepost

In the 16th and 17th centuries, astronomers tried to understand the motions they saw in the sky, motions we discussed in the last chapter. In doing so, they invented a new way of understanding nature, what we now call science. This chapter, then, is really about the birth of science.

Isaac Newton built upon the ideas of Galileo and devised ways to understand the motions of the planets and all objects in terms of gravity and his Laws of Motion. These basic ideas were later replaced by Albert Einstein's theory of gravity.

Historical Overview



Galileo and Motion

Galileo studied the motions of falling bodies, but not by actually dropping objects.
As an experimenter, he understood that the motion was too fast to accurately measure.

Galileo used polished bronze balls rolling down a gentle incline and an ingenious water clock to determine how long it took to fall.

http://en.wikipedia.org/wiki/Galileo_Galilei ; http://einstein.stanford.edu/SPACETIME/spacetime3.html

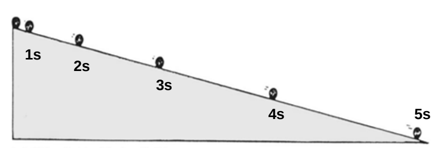
Galileo and Motion (2)

Galileo's genius was his recognition that his experimental results were proportional to those he would have obtained by dropping the balls.

Galileo discovered two important things with this experiment:

1. That objects accelerate as they fall; and
2. That mass makes no difference.

Galileo and Motion (3)



Objects rolling down an incline move faster as they fall – they accelerate.

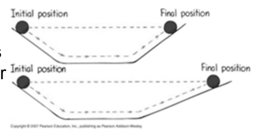
Galileo and Motion (4)

Another important discovery was this:

In the absence of a force, objects once set in motion tend to continue moving indefinitely.

Experiment:

Balls rolling down inclined planes and then up others tend to roll back up to their original heights.



Galileo and Motion (5)

Discovery:

In the absence of friction, *no force is necessary to keep a horizontally moving object moving*.

Conclusion:

The tendency of a moving body to keep moving is natural—every material object resists *change* in its state of motion. This property of things to resist change is called *inertia*.

A New Era of Science

Mathematics as a tool for understanding reality.

Isaac Newton (1643 - 1727)

- Building on the results of Galileo and Kepler
- Adding physics interpretations to the mathematical descriptions of astronomy by Copernicus, Galileo and Kepler

Major achievements:

1. Invented calculus* as a necessary tool to solve mathematical problems related to motion
2. Discovered the three laws of motion
3. Discovered the universal law of mutual gravitation

Newton's Laws of Motion

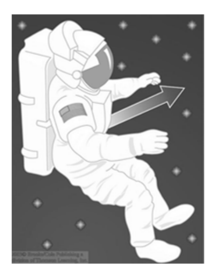
1. A body continues at rest or in uniform motion in a straight line unless acted upon by some net force.

An astronaut floating in space will continue to float forever in a straight line unless some **external force** is accelerating him/her.

Mass is a measure of an object's inertia.

Newton's Laws of Motion (2)

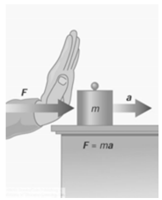
1. A body continues at rest or in uniform motion in a straight line unless acted upon by some net force.



An object continues to move because it has ***momentum***, which is related to its mass (inertia) and speed. Faster objects and more massive objects would have more momentum.

Newton's Laws of Motion (3)

2. The *acceleration* **a** of a body is inversely proportional to its *mass* m, directly proportional to the *net force* **F**, and in the same direction as the net force.

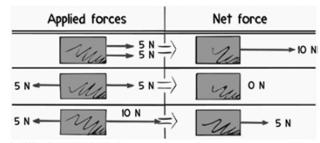


Acceleration occurs if either the speed or direction of motion changes. Net forces produce accelerations.

$\mathbf{a} = \mathbf{F}_{net}/m \Leftrightarrow \mathbf{F}_{net} = m\,\mathbf{a}$

Newton's Laws of Motion (4)

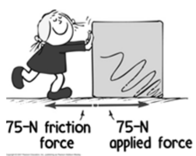
Net force is the combination of all the forces acting on an object. It can be positive, negative or zero!



$\mathbf{a} = \mathbf{F}_{net}/m \Leftrightarrow \mathbf{F}_{net} = m\,\mathbf{a}$

Newton's Laws of Motion (5)

If the net force is zero, the object is said to be in equilibrium. This means no acceleration, so an object can move at a constant velocity and still be in equilibrium!

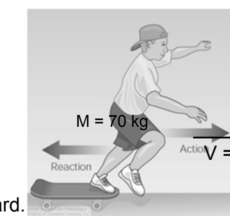


$\mathbf{a} = \mathbf{F}_{net}/m \Leftrightarrow \mathbf{F}_{net} = m\,\mathbf{a}$

Newton's Laws of Motion (6)

3. For every action force, there is an equal and opposite reaction force.

The same force that is accelerating the boy forward is accelerating the skateboard backward.



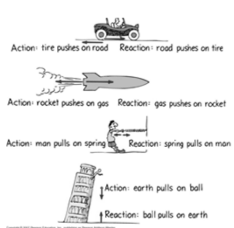
m = 1 kg

v = 7 m/s

Newton's Laws of Motion (7)

3. For every action force, there is an equal and opposite reaction force.

Forces come in pairs, each acting on the other object.

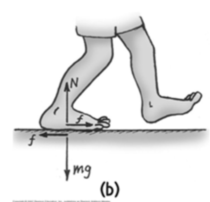


Newton's Laws of Motion (8)

Action and Reaction Forces:
Example – Walking

Balanced: Your weight (mg) and the normal force.

Unbalanced: Your foot pushes backwards on the floor; the floor pushes forward on you. Therefore – you go forward!



The Universal Law of Gravity

- Any two bodies are attracting each other through gravitation, with a force proportional to the product of their masses and inversely proportional to the square of their distance:

$$F = -G\frac{Mm}{r^2}$$

(G is the gravitational constant, $G = 6.67 \times 10^{-11}\ N\text{-}m^2/kg^2$)

The Universal Law of Gravity (2)

$$F = -G\frac{Mm}{r^2}$$

The greater m_1 and m_2 $\Rightarrow$ the greater the force of attraction between them.

The greater the distance of separation *d*, the weaker is the force of attraction—weaker as the inverse square of the distance between their centers.

The Universal Law of Gravity (3)

$$F = -G\frac{Mm}{r^2}$$

Inverse-square law: relates the intensity of an effect to the inverse square of the distance from the cause

$$Intensity \approx \frac{1}{distance^2}$$

The greater the distance from Earth, the less the gravitational force on an object.

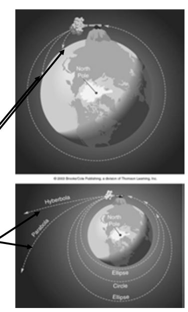
No matter how great the distance, gravity approaches, but never reaches, zero.

Orbital Motion

In order to stay on a closed orbit, an object has to be within a certain range of velocities:

Too slow => Object falls back down to Earth

Too fast => Object escapes Earth's gravity



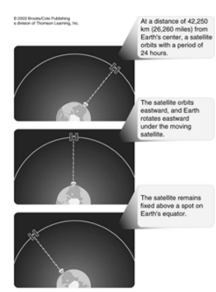
Orbital Motion (2)

The following concepts about orbiting objects are important:

1. An object orbiting Earth is actually falling towards the center of the Earth, but its *circular or angular velocity* allows it to remain in orbit. If the object slows down, then it would slowly spiral back towards the surface – something that happens occasionally.
2. The objects orbiting each other actually revolve around their mutual *center of mass*.
3. Closed orbits allow objects to continue to revolve about other objects; open orbits allow the object to escape (*escape velocity*).

Orbital Motion (3)

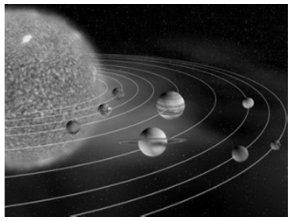
Geosynchronous Orbits



Orbital Motion (4)

The circular velocity of a planet is simply the circumference of the orbit divided by the orbital period, or

$$V = 2\pi r / P$$



http://www.scienceclarified.com/Ro-Sp/Solar-System.html

Kepler's Third Law Explained by Newton

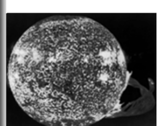
Balancing the force (called "centripetal force") necessary to keep an object in circular motion with the gravitational force → expression equivalent to Kepler's third law:

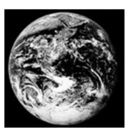
$$P_y^2 = a_{AU}^3 \longrightarrow P^2 = r^3 \frac{4\pi^2}{GM}$$

This is a powerful formula, as astronomers use it to calculate the masses of distant objects.

Tides and Tidal Forces

Question:
Where do the tides come from?





The Simple Answer:
Interactions between the Earth, Moon and Sun.

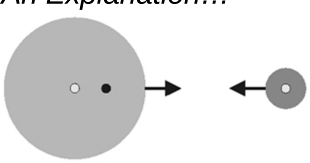
Tides and Tidal Forces (2)

The More Complete Answer:

The tides are a result of a complex interaction of gravity and centripetal forces between the three bodies, plus water depth, land mass locations, and the weather.

Tides and Tidal Forces (3)

An Explanation…

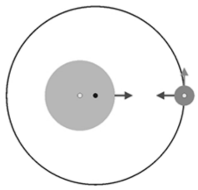


The Earth and Moon rotate about a center of mass that is located ~1720 km below the surface of the Earth (black dot), not about the center of mass of the Earth (yellow dot). The black arrows represent the mutual attraction of the gravitational force, which will be equal on each object.

Tides and Tidal Forces (4)

Rotation about a center of mass is not unlike the wobbly dance that a hammer thrower experiences as he/she rotates before the hammer is released. The thrower is like the Earth, and the hammer like the moon in this dance…

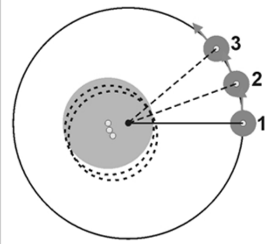
Tides and Tidal Forces (5)



The mutual gravitational attraction provides a centripetal force which keeps the two objects orbiting about their common center of mass.

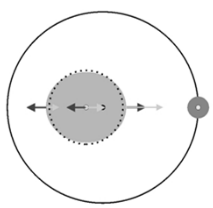
The orange arrow represents the rotational force on the system. The red arrows are the centripetal force provided by gravity. The centripetal force keeps the Moon orbiting the Earth.

Tides and Tidal Forces (6)



As the moon orbits around the Earth, the centripetal force keeps the entire system rotating about the center of mass.

Tides and Tidal Forces (7)



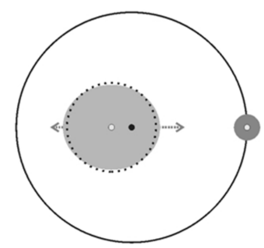
This force not only affects the Earth but the oceans surrounding the planet also. The oceans, being a fluid, respond more to the attraction, and a tidal bulge develops (blue).

The forces acting on the Earth and its oceans are unbalanced, with the centripetal force (red) not being the same as the gravitational force (green) except at the center of the Earth. The <u>net force</u> creates the bulge
… or does it?

Tides and Tidal Forces (8)

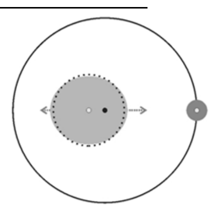
No matter how large this net force (green) is, the Earth's gravity field is greater, which means the water <u>should not bulge at all</u>.

But it does! Why??



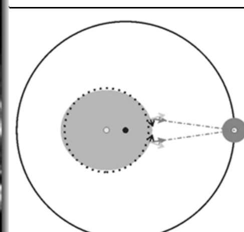
Tides and Tidal Forces (9)

In the analysis, we only considered the effect of gravity directly beneath the Moon's location (called the sublunar point) and at the point directly opposite (the antipodal point).



In order to explain the tidal bulge (and the depression in the water at 90^o from these locations, we need to look more closely…

Tides and Tidal Forces (10)



The net forces at points away from the sublunar and antipodal points have a component that is parallel to the surface of the Earth (blue arrows)

This portion of the net force is <u>not</u> counteracted by Earth's gravity and forces the water to flow towards the sublunar and antipodal points and away from the regions in between (making the "low tides").

Tides and Tidal Forces (11)

As the Earth rotates on it's axis, the position of the bulge (and depression) moves around the Earth, allowing the high (and low) tides to visit different locations throughout the day.

At some places, the difference in high and low tides can be extreme (Hopewell Rocks, Bay of Fundy, New Brunswick, Canada)

Tides and Tidal Forces (12)

Other factors…

Other factors contribute to the complexities of the tides. These include the following:

- Tilt of the Moon's orbit (5^{o})
- Tidal Day (~24 hrs 50 m) vs. Solar Day
- Addition of Sun's gravity makes the bulge either lead the Moon or lag behind it. The tidal bulge will *lead* the Moon between New and 1st Quarter phases and Full and 3rd Quarter phases; it will lag behind the Moon between 1st Quarter and Full Moon, and 3rd Quarter and New Moon (by up to 2 hours).

Tides and Tidal Forces (13)

Other factors…

- Land masses prevent the water from flowing freely around the Earth.
- Changes in water depth slow down the water and oceanic topography can channel it.
- Narrow openings can lead to very large changes in the tides.
- Weather changes, such as high pressure (lower tides) or low pressure (higher tides) can contribute to the tidal range.

Other effects of the tides:

- The effect of the Earth's gravity on the Moon has caused the Moon's rotation rate to slow until it is equal to its orbital rate, therefore the same face always looks at us.
- Our days are getting longer due to tidal friction at a rate of 0.0015 seconds per century.
- Tidal forces also cause the Moon's orbit to recede from the Earth at a rate of 3.8 cm per year.

Conclusion

The tides are a result of a complex interaction between the various things (gravity, centripetal forces, fluid behavior, land masses and their shape, the weather, etc.) and this leads to a wonderfully difficult time in predicting when tides will occur and how high they will be.

Check this out!

Astronomy After Newton

Newton's great work, the *Philosophiae Naturalis Principia Mathematica (1687)*, changed astronomy, science and the way people think about nature.

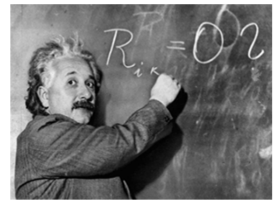
Astronomy was changed because Newton's Laws of Motion and his gravitational formula gave astronomers the ability to understand and predict motions in the solar system and beyond.

Astronomy After Newton

Science was changed because the *Principia* showed the true power of mathematics to describe the natural world.

Our ideas about nature were also changed because the *Principia* showed the rules that govern the universe are simple; motions are predictable and the past and future history of the universe could be derived from basic principles.

Einstein and Relativity



Albert Einstein (1879-1955) was one of the greatest scientists of all time. His thinking about motion and gravity allowed for a revision of the nature of Newton's ideas on gravity called *Special and General Relativity*.

http://www.lsw.uni-heidelberg.de/users/mcamenzi/Week_2.html

Einstein and Relativity (2)

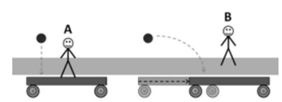
Special Relativity is based upon two primary principles or postulates:

1. "Observers can never detect their uniform motion except relative to other objects." Another way of saying this is that "the laws of physics are the same for all observers so long as the observers are not in an accelerated reference frame."

What this means is that different observers will see different things depending on their frames of reference.

Let's look at an example…

Einstein and Relativity (3)



Observer A is on the train, while Observer B is on the platform. A ball is dropped on the train. To Observer A, it appears to fall straight downward. To Observer B, however, the ball looks like it follows a parabolic path – just as if someone had thrown the ball. In other words, the result is *relative* to your frame of reference – where you make your observations from.

http://infanthercules.wordpress.com/tag/special-relativity/

Einstein and Relativity (4)

Special Relativity is based upon two primary principles or postulates:

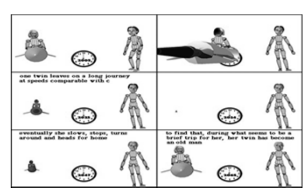
2. "The speed of light is constant and will be the same for all observers independent of their motion relative to the light source."

The second postulate is required by the first. If this were not true, the speed of light would be different depending on where you did your measurement.

Einstein and Relativity (5)

The combination of the two postulates of relativity leads to interesting results:

Objects moving at speeds approaching the speed of light (300,000 km/sec) gain mass, get shorter and time stretches out for these objects. This leads to results such as the Twin Paradox:



http://www.phys.unsw.edu.au/einsteinlight/jw/module4_twin_paradox.htm/

Einstein and Relativity (6)

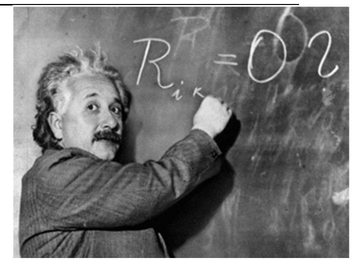
The combination of the two postulates of relativity leads to interesting results:

The other result is that the energy of a motionless particle is not zero – there is a relativistic energy related to its rest mass and the speed of light, or

$$E = mc^2$$

The amazing part of this is that mass and energy are one in the same – there is Conservation of Mass-Energy, not just energy by itself.

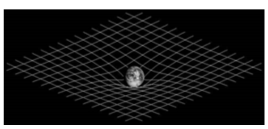
Einstein and Relativity (7)



General Relativity is a much more advanced theory and in fact is a theory that explains how gravity really works.

Einstein and Relativity (7)

The first principle of General Relativity states that pure acceleration and gravity can't be distinguished from one another, meaning that an observer in a windowless spaceship can't tell if they're on a planet with gravity or accelerating in space.



The second principle is that mass creates curvature in space-time, and this curvature results in the acceleration of nearby masses.

http://www.cuemath.com/wp-content/uploads/2012/10/022009hej1.jpg

Einstein and Relativity (8)

Einstein's General Theory of Relativity made several predictions that have been confirmed through observation and experiment:

1.
The advance in the perihelion of Mercury. Observations showed that the orbit of Mercury was "wobbling" and the point of closest approach to the sun was migrating; relativity predicts this advance nearly perfectly.

Einstein and Relativity (8)

Einstein's General Theory of Relativity made several predictions that have been confirmed through observation and experiment:

2.
Light can be curved by large masses, such as a star. Observations of stars around the Sun during a total solar eclipse show them to be displaced by the exact amount predicted by theory.

Einstein and Relativity (8)

Einstein's General Theory of Relativity made several predictions that have been confirmed through observation and experiment:

3.
Because light can be affected by curved space-time, if enough mass is present, a black hole can develop. Indirect observations of black holes have been made.