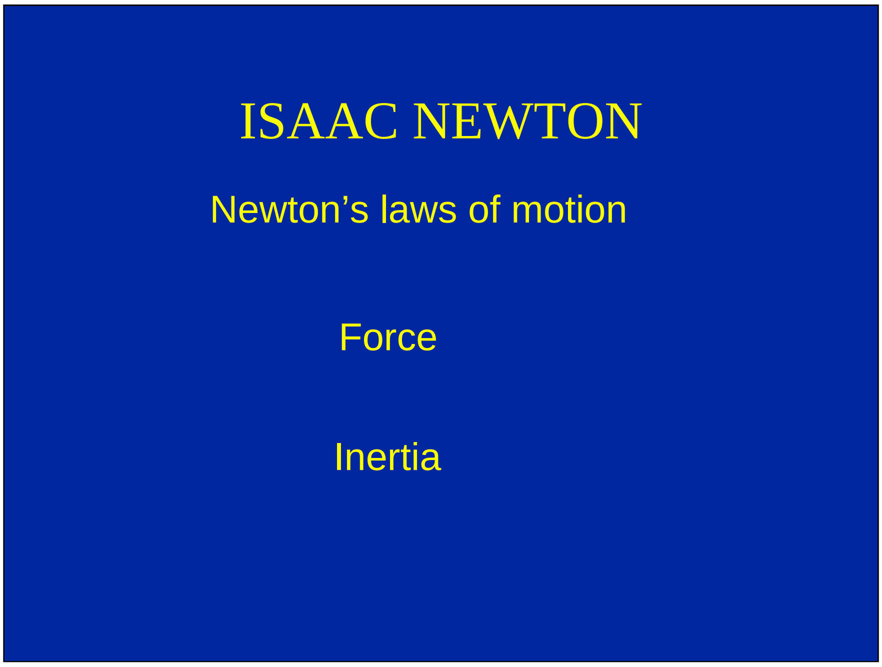


Now that we know how to describe motion, we are ready to learn what causes it. Newton was the person who solved this problem for us, writing three laws of motion that allow us to understand the motions of billiards on a table, and the planets around the sun. These laws are remarkable precise.

All the motions that we encounter in everyday life can be understood by Newtonian mechanics. These laws only run into trouble in environments far different than we normally encounter: speeds approaching the speed of light, and elementary particles such as an individual electron.

In physics we use the term force much as we do in everyday life: A push or a pull acting on a body. Inertia is the property of a body that resists changes in velocity. It is measured by the body’s mass.

As we will see, Newton used our solar system as a laboratory to develop his laws of motion and understanding of gravity. Kepler’s empirical laws describing planetary motion were the proving ground for his basic results.

NEWTON VS GALILEO

Galileo:

Natural Horizontal: v = constant unless a force

Natural Vertical: a = constant

Newton:

In any direction: v = constant when F = 0

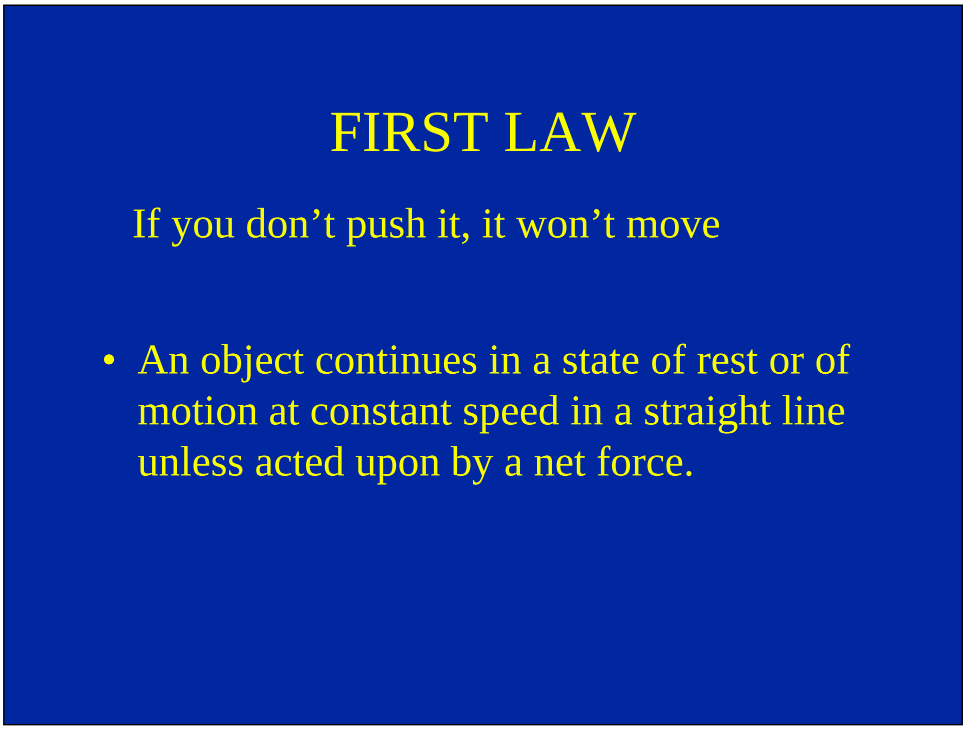
Forces cause acceleration

Galileo treated motion near the surface of the earth as occurring in two distinct “natural” categories. Horizontal motion, if friction can be removed, would consist of constant speed in a straight line. As we saw, he came to this conclusion by working with very round rolling balls and hard smooth surfaces.

“Natural” vertical motion on the other hand, exhibited constant acceleration. As we saw he established this with his inclined plane experiment.

Galileo’s use of the term “natural” has an Aristotelian ring to it. Aristotle wrote that the natural motion for a dropped rock was to move downward, towards where it belonged with the other rocks in the earth. Galileo argued against many of Aristotle’s ideas, but seemed to remain imprisoned by this categorization.

In Newton’s mind, vertical and horizontal motion were just two examples of the same thing. With no applied force, v = constant. With an applied constant force, a = constant. So Newton started where Galileo left off, generalizing his ideas about motion, and as we will see, did so in a quantitative way.



Newton’s first law appears the same as Galileo’s principle of inertia, but is is a broader statement, because for Galileo it only applied to the special case of horizontal motion on a hard smooth surface. For Newton it applies to motion in any direction.

For example astronauts in a weightless environment see this law in action all the time. A pencil will hover motionless in the middle of the cabin until it is pushed.

Note that zero velocity and non-zero velocity are treated on the same footing. This is consistent with Galileo’s principle of relativity according to which uniform velocity has no absolute meaning, since it depends on the observer. Zero velocity just means the observer is moving along with the object. (eg astronaut example).

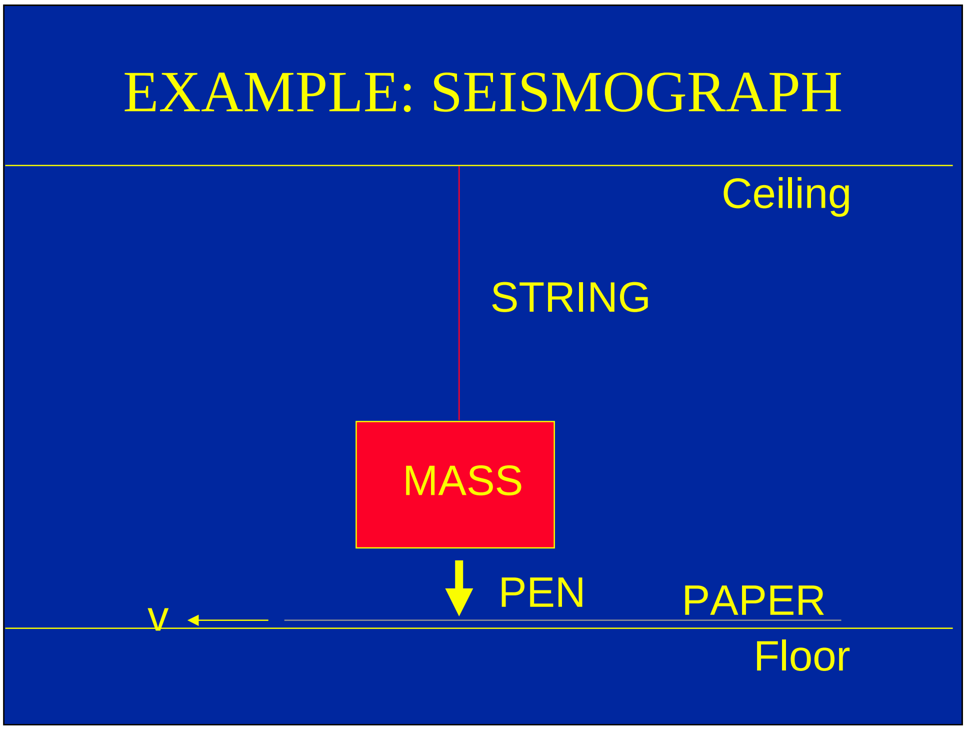
The inertia of a body resists changes in its motion.

SHOW table cloth jerk

SHOW pencil, hoop, coke bottle

SHOW hanging mass and breaking string

SHOW hammer and anvil.



Here is a conceptual model of a seismograph. When an earthquake occurs, the ground moves back and forth. We would like to measure that motion, but since we are standing on the ground, we move back and forth with it. What we need is an independent body that doesn't move with the ground.

Hang a mass from the ceiling by a string. Then when the ceiling and floor move, the mass will not move with them. The horizontal force applied to the mass by the string will be small if the string is long, so the inertia of the mass keeps it nearly stationary. Then the pen traces out the motion of the floor relative to a stationary object, the hanging mass.

Which component of the floor motion does the seismograph record?

NEWTON'S SECOND LAW

$$a = F/m$$

F = sum of all external forces acting on the body = net force

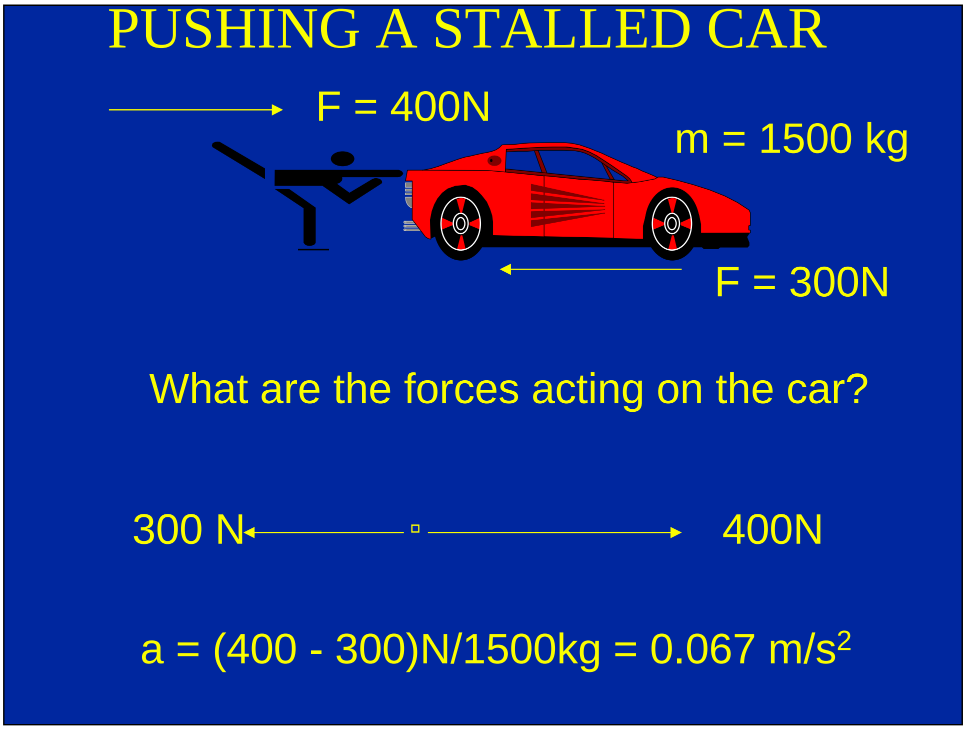
System	Mass	Acceleration	Force
SI	kg	m/s^2	newton (N)
CGS	g	cm/s^2	dyne (dyn)
BE	slug (sl)	ft/s^2	pound (lb)

Newton's second law is much more general than the first. It tells us what happens when forces acting on a body *are* present. A net force acting on a body from the environment produces an acceleration of the body.

The inertia of the body, as measured by its mass, resists the change in velocity caused by the force. The greater the mass, the smaller the acceleration.

It is simplest to think about Newton's laws in the absence of friction. We can take friction into account, however, by including it as one of the forces acting on the body of interest.

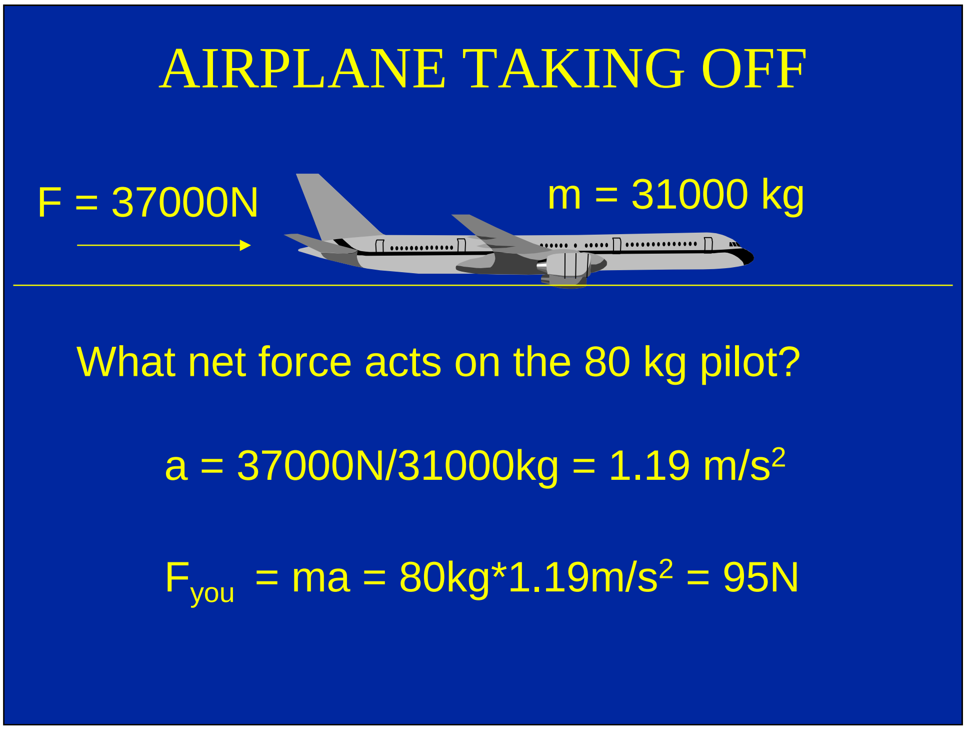
SHOW Propeller driven glider timed for one unit of distance and four units. Since it takes twice as long to go four times as far, the acceleration must be constant. So the propeller is providing a nearly constant force, leading to a constant acceleration.



This fellow is pushing his stalled car along a level street. It has a mass of 1500 kg, and is resisting his efforts with a friction force of 300 N caused by the distortion of the tires as they rotate, and any other source. He pushes with a force of 400 N.

To handle problems like this it is useful to draw a diagram that includes only the forces being applied to the object from the environment. For simplicity, the drawing need (should) not be realistic such as the picture of the car above. Just use a small square or a dot to represent the car. Then add the forces, representing their directions by arrows to find the net force, and evaluate the acceleration.

Here we are assuming that all the forces are constant, which in a realistic situation they are unlikely to be. We can think of these forces as average values.



An airplane is accelerating down the runway for takeoff. Its engines provide a thrust force of 37000 N, and the mass of the airplane, including everything in it, is 31000 kg. You are sitting in one of the passenger seats facing forward. Assuming your mass is 80 kg, what is the net force on you?

From the numbers given, the airplane is accelerating at 1.19 m/s^2. So you are sitting in a seat that is accelerating. What is the net force applied to each of you now as you sit in your seats? Gravity is pulling you downward and your seat is pushing you upward. They evidently add to zero since you are not accelerating.

In the airplane you are accelerating however, so there must be a net force acting on you. The seat is pushing you forward causing you to accelerate, a force you have doubtless noticed sitting in a car seat or an airplane seat. The forward-directed net force needed is 95 N.

SERVING A TENNIS BALL

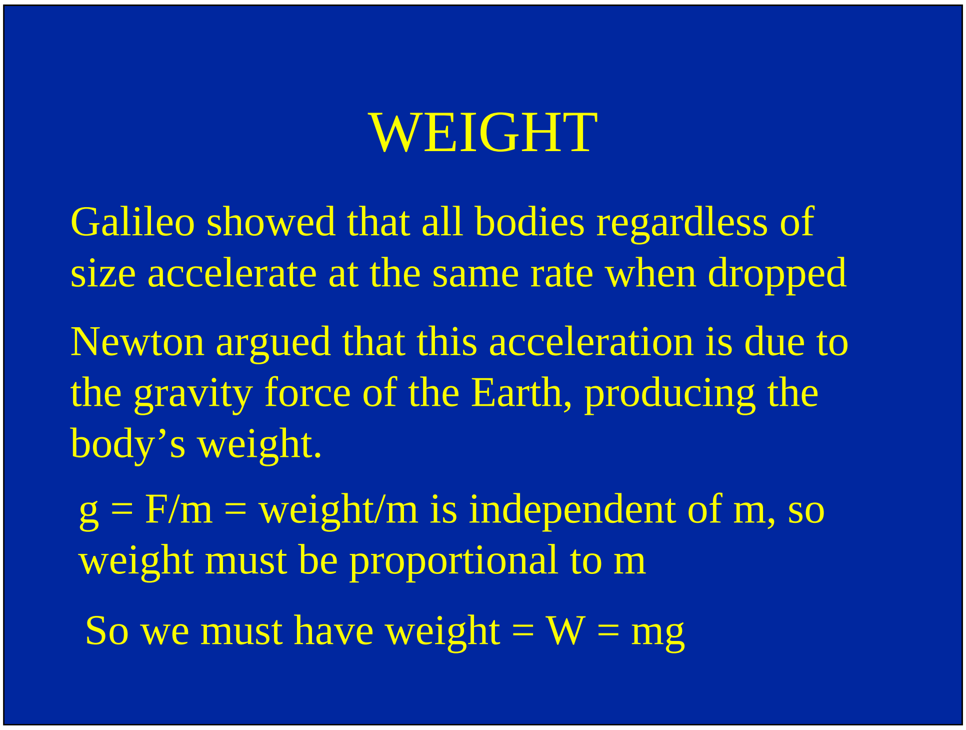
- A 0.058 kg ball is accelerated to speed 45m/s while it is in contact with the racket for 0.018 s. What average force does the racket exert on the ball?
- $a = v/t = 45/(.018) = 2500 m/s^2$
- $F = ma = 0.058 kg * 2500 m/s^2 = 145 N$
- How far does it go while it is in contact with the racket?
- $x = 1/2at^2 = ½(2500)(0.018)^2 = 0.4$ m

When a tennis ball is served, the racket and ball are in contact for only a short time, and the ball is accelerated up to speed quickly. Here are some numbers giving us a quantitative picture of this event.

To find the force, what is it we need to know? The acceleration. We know the contact time and final velocity, so our most direct route to a is this relation.

Now knowing a we can easily find F (145 N = 32 lb).

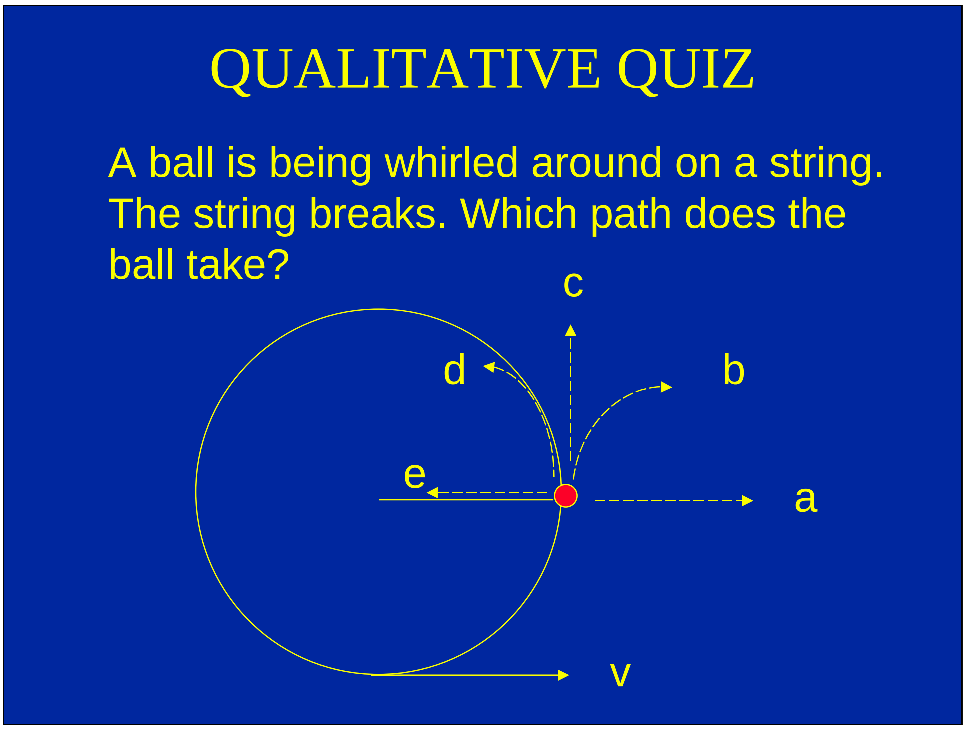
How far did the ball go while it was in contact with the racket? 0.4 m is a reasonable fraction of the swing distance. This is why spin can be put on the ball.



Here we bring together Newton's ideas about force and acceleration with Galileo's results for falling bodies. If all acceleration is due to a force, in this case the weight of a body caused by the earth's gravity, and if all bodies accelerate at the same rate, then it must be that a body's weight is proportional to its mass.

That proportionality constant must be g, the acceleration due to gravity.

This is a non-trivial result. It says that mass has two meanings: It is the property of a body that resists change in velocity (inertial mass), and it responds to a gravitational pull (gravitational mass). Experimental tests have shown that the gravitational and inertial masses are equal to a very high precision.



Ignore all other forces except that of the string acting on the ball. At a certain moment when the ball is at the position shown in the picture, the string breaks. What path does the ball take immediately after?

What principle can we use to answer this question? What idea is involved?

When the string breaks the ball is moving straight up in the picture, and there are no forces acting on it. So it keeps moving in the same direction in a straight line with constant velocity.

NEWTON’S THIRD LAW

Forces always occur in equal and opposite pairs. An isolated single force does not exist in our universe.

Whenever one body pushes on another, the second body pushes back with an equal and opposite force.

Newton was the first to realize that forces always come in pairs. When I push on this table, I am applying a force in a downward direction to it. But the nerves in my hand tell me that the table is pushing up on my hand. Indeed if it were not, then I would fall over.

An example of a propulsion devise that uses Newton’s third law is a propeller. When a propeller spins it pushes air backwards. I can feel the air being blown backwards by this glider propeller. But when the air is pushed backwards, it exerts an equal and opposite force on the propeller, pushing it, and the glider, forward.

SHOW water rocket. Here the air pressure pushes water backwards out of the rocket. As it leaves, the water exerts an equal and opposite force on the rocket, pushing it forward.

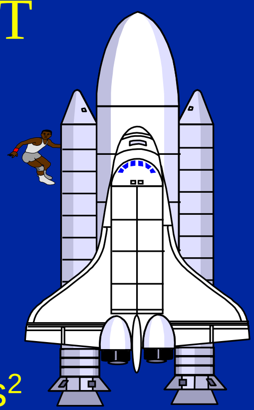
SHOW fire extinguisher rocket cart. Comment on the loud noise made by the turbulent air. Turbulent air produces a wide range of sound frequencies we can hear. Some musical instruments, such as the flute, use this turbulence to make musical sounds.Only certain frequencies are amplified by the structure of the flute, so they are the only ones we hear (if the flutist is good). (Illustrate with coke bottle).

ASTRONAUT PUSHES SPACECRAFT

$F = 40$ N
$m_a = 80$ kg
$m_s = 15000$ kg

$a_s = F/m_s = 40\text{N}/15000 \text{ kg}$
$= 0.0027 \text{ m/s}^2$

$a_a = -F/m_a = -40\text{N}/80\text{kg} = -0.5 \text{ m/s}^2$



If $t_{push} = 0.5$ s, then $v_s = a_s t_{push} = .0014$ m/s, and
$v_a = a_a t_{push} = -0.25$ m/s.

An astronaut is floating around outside a spacecraft and gives it a push. Newton’s third law says that if he pushes on the spacecraft, it will push back on him with an equal and opposite force.

The spacecraft and astronaut will both be accelerated since there is a net force on each, and they will drift apart. They move at different rates, however, since they have different masses.

The velocity of both spacecraft and astronaut after the push is over will equal their accelerations during the push times its duration.

The same thing happens when the astronaut is inside the spacecraft. After pushing on a wall, he/she will float away, and the ship accelerates also. One of the things astronauts must adjust to is to push on walls they encounter gently, since a hard push gives them too much velocity for comfort.

NEWTON'S LAWS IN EVERYDAY LIFE

You are standing still, then begin to walk. What was the external forced that caused you to accelerate?

Hint: It is very hard to start walking if you are standing on ice.

What force causes a car to accelerate when a traffic light turns green?

The second law states that whenever a body accelerates, an external force must be present to cause the acceleration. It is not always obvious what this force is even in very ordinary circumstances.

In order for you to accelerate forward when you start walking, something must push you forward. What is it? It must be the sidewalk. You push back with your feet, and the sidewalk pushes you forward by an equal amount according to Newton's third law. This could not happen without friction.

You may think that it is your pushing against the sidewalk that causes you to move forward, but it is really the sidewalk pushing forward on you.

Same argument for a car accelerating.

NEWTON AND THE APPLE

Newton knew that at the surface of the earth bodies (apples) fall 5 m in the first second, and that this acceleration is due to earth's gravity.

He showed that the gravity force is the same as if all earth's mass were at its center, 4000 mi from the surface.

He wondered whether the same force attracts the moon towards earth.

There is a story you have probably heard that Newton was stimulated to think of his Universal law of Gravitation by seeing an apple fall at his mother's farm in Woolsthorpe. This might even have happened.

At that time a gravity force was being thought about by several people and commonly thought to decrease inversely as the square of the distance between the two objects attracting each other.

The earth and the apple attract each other resulting in the acceleration studied by Galileo. Does the same force, reduced by the square of the distance, cause the moon to fall towards the earth?

Does the moon fall towards the earth? It remains the same distance away, so at first it does not seem to do so, but let's look more carefully into this.

ACCELERATION OF OBJECT MOVING IN A CIRCLE

Speed is rate of motion without regard for direction. A car goes 60 mph.

But to tell where the car goes, direction must be specified as well as speed.

The term velocity is used to describe both speed and direction.

Acceleration in Newton's second law, is the rate of change of velocity, not just speed.

The acceleration of an object is its rate of change of velocity, not just speed. For example a car going around a corner at a constant speed of 25 mph is accelerating, and you as a rider in the car feel that acceleration. The seat of the car must push on your body to make it accelerate.

Turning left, the car seat must push you to the left.

The moon is moving (nearly) in a circle about earth with constant speed. That means its velocity is constantly changing. If it were not, it would continue in a straight line. So it is accelerating.

Let's see if we can understand the magnitude and direction of that acceleration. This means we want to study objects that move uniformly in a circle.

UNIFORM CIRCULAR MOTION

- Centripetal Acceleration
- Centripetal Force
- Example: The moon

In studying uniform circular motion we will be using the same ideas of kinematics (x, v, a) and Newton's Laws of motion that we have been studying, but we will apply them to situations involving motion in circles.

A new word in involved: Centripetal. This just means directed towards the center. A centripetal acceleration is one directed towards the center of the circle in which an object is moving.

Roller coasters at amusement parks use circular motion to achieve apparent weightlessness momentarily. This can occur near earth where g is still strong, but the object behaves in some ways as if it were far from any star or planet.

Uniform Circular Motion is the motion of an object traveling at constant speed in a circular path.

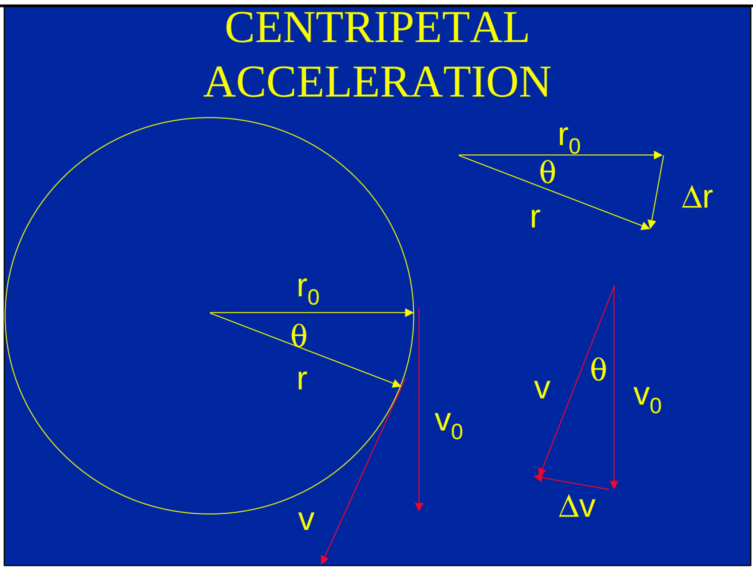
Examples:

- spot on a phonograph record
- washing machine during spin cycle
- ball whirled around on a string
- car turning a corner
- moon in orbit around Earth

The definition of uniform circular motion is very simple. There are many examples such as these. Many others involve such things as a centrifuge, any motor with a rotating shaft...

Since the same ideas can be used to describe such a wide range of phenomena, they will prove to be very useful.

In all of these examples the speed, but not the velocity is constant. The magnitude of the velocity is constant but its direction is constantly changing.



Here we have an object moving in a circle with a constant speed. Why is there any acceleration? Simply because velocity is a vector quantity, and in this case, its magnitude doesn't change, but its direction does.

Consider our moving object at two times: It has moved from r zero to r. Here I have moved the two r vectors away so we can see them more easily. The change in r is delta r as shown.

Since the position is changing with time, there is a non-zero velocity. The velocity vectors are shown in red. The velocity is perpendicular to the radius vector at all times during uniform circular motion. The velocity is always tangent to the circle describing the motion.

But in that case, the velocity itself is rotating around in a circle just like the radius vector. Here I have moved the two velocity vectors away so we can see them also. Because v is always perpendicular to r, the angle between the two r vectors is the same as that between the two v vectors.

This means that the r triangle is similar to the v triangle. They have the same shape. One thing that means is that the ratios of corresponding sides are equal. We also see that as Δt (ie θ) becomes small, Δv is perpendicular to v just as Δr is perpendicular to r.

$$a_c = v^2/r$$

$\Delta r/r = \Delta v/v$

And, $\Delta r = v\Delta t$ so

$\Delta v = v(v\Delta t)/r$

$\Delta v/\Delta t = v^2/r$

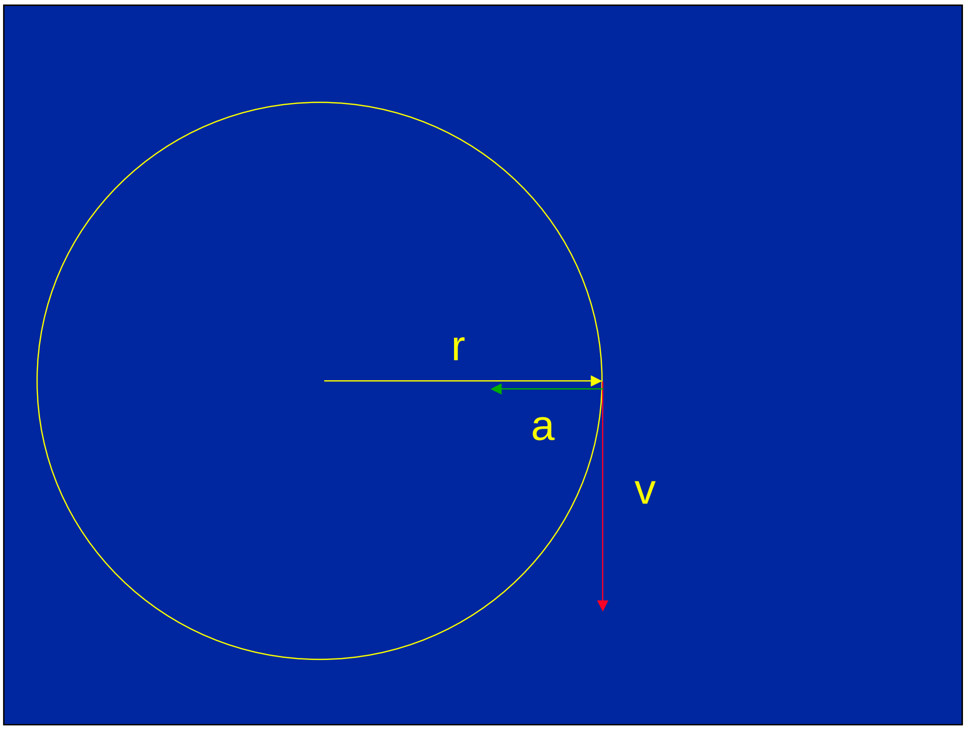
Centripetal Acceleration = a_c

$a_c = v^2/r$

The centripetal acceleration points radially inward toward the center of the circle.

From the similarity of the triangles we see that the change in r divided by r is equal to the change in v divided by v during the same small time interval Δt. This allows us to solve for the centripetal acceleration magnitude as shown. This is a very simple and useful result: Whenever an object moves in uniform circular motion, it is undergoing an acceleration equal to v^2/r.

But a is a vector also. What direction does it point? Looking at the previous slide we can see that a must be perpendicular to v just as v is perpendicular to r in the limit as theta (delta t) gets very small.



Here we show the relative orientations of r, v, and a that we have just established for uniform circular motion. This is quite different from our linear F = ma problems so far, where the relative orientations of these vectors could be anything depending on the circumstances.

In this way uniform circular motion is simpler than linear motion problems.

SHOW rotating table with accelerometer on it. This clearly shows that there is an acceleration whose magnitude can be maintained nearly constant, but whose direction rotates around with the table.

BALL ON STRING

- r = 0.5 m, T = 2 s. What is a_c?
- $v = 2\pi r/T = 3.14/2 = 1.6$ m/s
- $a_c = v^2/r = 2.5/0.5 = 5$ m/s^2
- What if we cut the period in half?
- a_c quadruples to 20 m/s^2

Here is a game we have all played: Whirl a ball around on a string. Let us define T to be the period of the motion ie the time for the ball to go around one time. As long as we keep it moving with a constant period and radius, it is exhibiting uniform circular motion. For the given radius and period, what is the magnitude of the centripetal acceleration?

We know the radius, so all we need is the speed. How do we find that? The period is the time for one round trip, ie one time around the circle. How far does the ball go during one period? Just the circumference of the circle. So the speed (magnitude of the velocity) is 2 pi r divided by T which is 1.6 m/s in this case.

Then the centripetal acceleration is just the velocity squared divided by the radius, or 5 m/ss.

Question: What if I speed the ball up so as to cut the period in half. What is the centripetal acceleration now?

Centripetal Force

- The name given to the net force needed to keep a mass m moving with speed v in a circle of radius r.
- Magnitude: $F_c = mv^2/r$
- Toward the center of the circle

Newton tells us that when there is an a there will be an F. The centripetal force is not a new special kind of force, like friction, or gravity. It is simply the name we give to whatever force exists in a situation where uniform motion in a circle is taking place, that causes the object to move in that way. It must always point toward the center of the circle, and have a constant magnitude as long as v and r remain constant.

In the example of the ball on the string we just saw, the centripetal force is provided by the string tension.