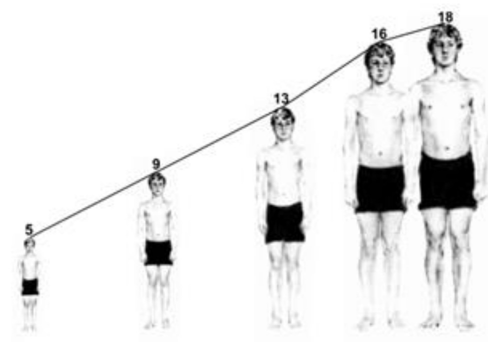
Fascinating Education Script
Introduction to Science Lessons

Lesson 5: Newton's Laws

Slide 1: Introduction

Slide 2: Introducing charts

From age 5 to about age 13, you grow at a steady rate. From age 13 to 16, you undergo a growth spurt and then slow down again until you reach your final adult height.

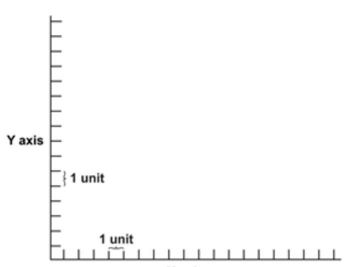


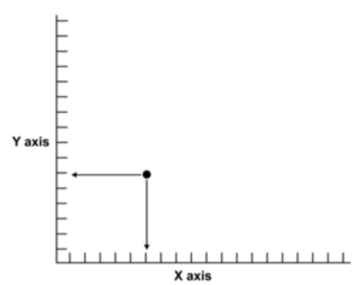
Suppose from age 5 to 13, you grow at about 5-6 centimeters a year, from age 13 to 16 you grow around 7 or 8 centimeters a year, and then drop back to 3 to 4 centimeters a year between 16 and 18 years of age. How would you show this in a graph?

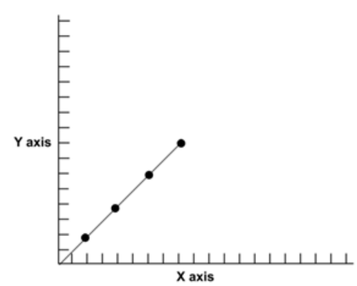
Slide 3: Let's explain graphs.

Here is a blank graph. The horizontal line is called the X axis and the vertical line is called the Y axis. Each axis is divided into units.

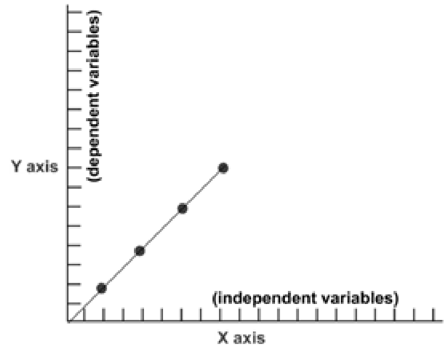
Any one point in the graph tells you that when X is this, Y is that. And vice versa: when Y is this, X is that. You can always add points to a graph if you know the values of X and Y at a particular moment. With enough points, you can make a graph line.



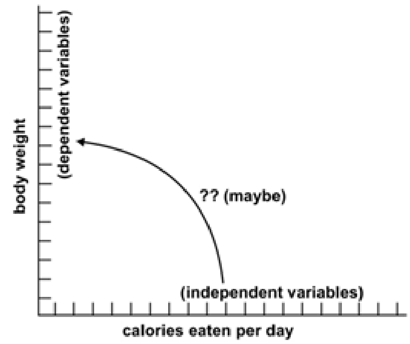




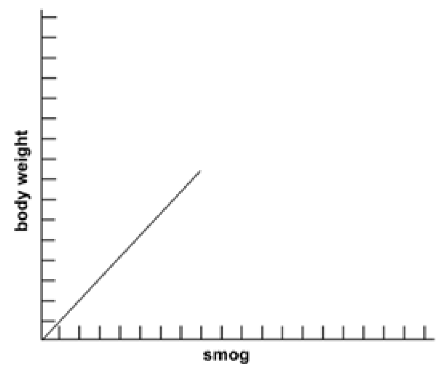
To make sure everyone knows which axis we're talking about, we call the numbers along the X axis the independent variables, and the numbers along the Y axis, the dependent variable.



At first glance it may look like things along the X axis are causing the values along the Y axis. It sure makes sense that the more calories people eat per day, the more they weigh, but don't get suckered into thinking that a graph proves that the X axis is causing the Y axis. All a graph shows is that when X changes, Y seems to change, too. X could be causing Y to change, or Y could be even causing X to change, but both could be increasing or decreasing because of some third factor affecting them both.

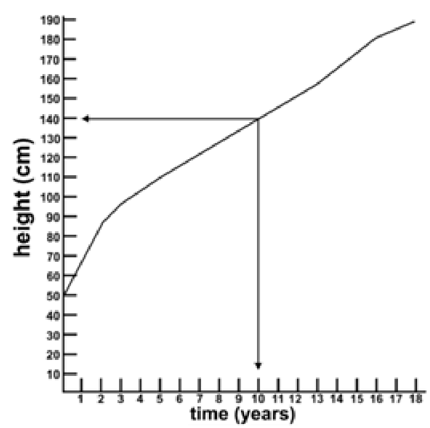


For example, X could be levels of smog in the air, and Y could be the average weight of people in the general population. Both are increasing, but not because smog is causing obesity, or because obesity is causing smog. The simultaneous increase of both smog and obesity could be due to a third variable: the increased use of automobiles to get around.



Slide 4: Variables on a chart

So, let's chart a young man's growth. Here is a blank graph. What units should we put along the X and Y axes?



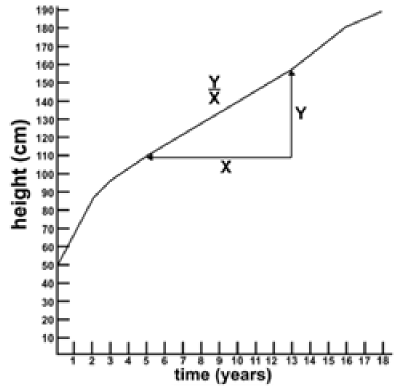
The two variables for growth are time and height. Which is the independent variable, and which is the dependent variable? We tend to think of time changing first and a person's height depending on the passage of time, so let's make time the independent variable along the X axis, and height the dependent variable along the Y axis. We'll make the units of time along the X axis in years, and the units of height along the Y axis in centimeters.

Here is the young man's growth up to age 18. What does the graph line tell you?

Every point along the graph line tells you his height in centimeters for each year.

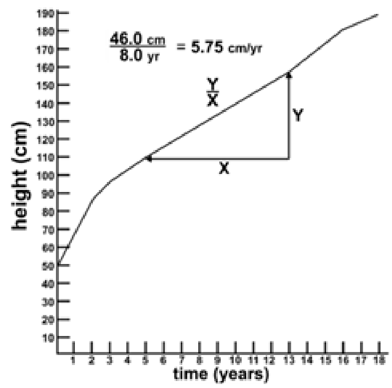
What does the slant of the graph line tell you?

The slant of any graph line represents the Y axis divided by the X axis. What would the units for the slant of the graph line be in our growth chart?



Centimeters per year. That's the units, but what numbers do you use?

The slant of the graph line is Y over X, so count however many years you like and measure what happens to the height in those years. In our example here, between the years of 5 and 13, 8 years total, this young man's height rose 46cm -- from 108cm to 154cm. What is the slant of the graph line?



The slant of the graph line is Y over X. No matter how long a section of X you choose, so long as that graph line is a straight line, Y over X is always the same. If for example, we choose the entire period of 8 years from 5 to 13, we see that Y rose 46 centimeters. Y over X is 46 centimeters divided by 8 years, or 5.75 centimeters per year.

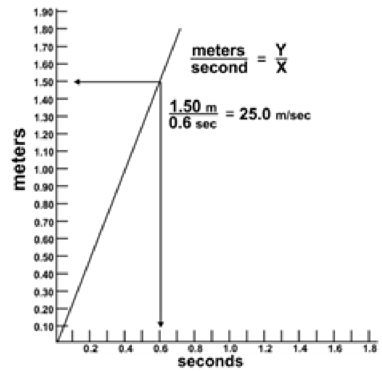
What does the "per" mean mathematically?

Per means draw a line and divide whatever came before the per by whatever came after the per.

5.75 centimeters per year is the growth rate between the ages of 5 and 13. Because the graph line is straight between the ages of 5 and 13, the slope remains the same everywhere along that section of the graph line. That means his growth rate remained constant during those years.

If you know that you are graphing, say, speed in meters per second, you immediately know that the units in the numerator – meters -- belong along the Y axis, and the units in the denominator – seconds -- belong along the X axis.

The slope of the graph line is Y over X, or meters per second. If the slope of the graph line never changes, it means that the speed is remaining constant.
Even if you are measuring over very short periods of time, the ratio of Y over X will always work out to be, in this case, 25 meters per second.

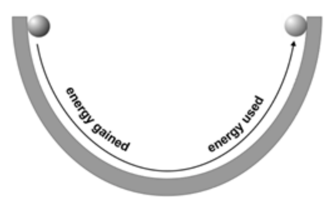


Slide 5: Who is Galileo Galilei?

We are going to use graphs to help us analyze the movement of a marble as it rolls down this U shaped track. This experiment was performed about 400 years ago, around 1600, by Galileo Galilei. Galileo constructed a U shaped track, like a skateboard track, and then rolled a marble down one side of the track. Not surprisingly, the marble rolled up the other side of the track to the same height.

He found that the marble always rolled to the same height no matter what height he released the marble from.

What conclusion do you draw from the fact that no matter what height the marble was released from, it always rolled back up the other side to the same height?

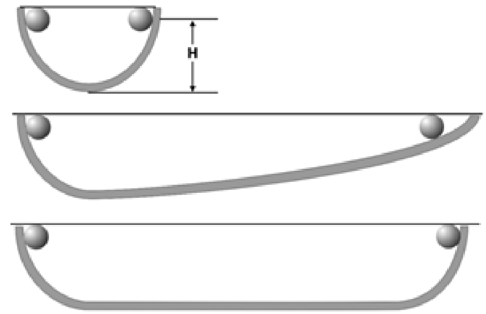


The same conclusion that Galileo drew. Whatever energy the marble gained from the force of gravity during its fall …. it used up that energy in climbing to the same height on the other side.

Slide 6: Understanding conclusions

The next thing Galileo did was bend the track so that the marble would have to travel farther in order to reach the same height. Where do you think the marble stopped – at the same height it was originally released from, or at some point lower than its original height?

No matter what shape he made the track, or how long he made the track, the marble always rolled back up to the same height.

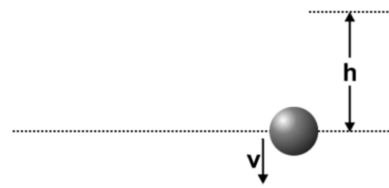


Can we still stick to our previous conclusion that energy in equals energy out?

Yes, so long as we say that energy in only depends on how high off the ground we release the marble, represented by the letter H.

Slide 7: Confirming your hypothesis

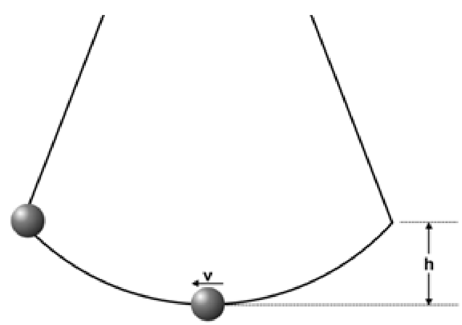
Does that make sense? Is the height off the ground the only thing that determines how much energy an object has?
Here is an experiment that might help confirm our hypothesis.



Suppose we lift this metal ball a distance, H, and drop it. By the time the metal ball strikes the floor, it's traveling a certain velocity, V. The only thing that determines it velocity when it hits the ground is how high off the ground it was when it was released. The velocity of the metal ball, then, is a measure of how much energy we put into it by lifting it off the ground.

Now, instead of dropping the marble, suppose we attach it to a string and make the metal ball swing like a pendulum. We lift the ball to the same height, H, and release it. What does our hypothesis predict the speed of the metal ball when it swings past the bottom of the arc?

If the height we lift the metal ball is a measure of how much energy we put into the metal ball, both metal balls should have the same amount of stored up energy, because we lifted both metal balls to the same height.



As the pendulum swings through the bottom of its arc, all that energy is released to speed the ball along. Since the metal ball on the pendulum falls the same distance as the metal ball that was dropped, what does our hypothesis predict?

Yes, it predicts that the horizontal velocity of the metal ball swinging through the bottom of the arc should be the same as the velocity of the dropped ball when it strikes the ground, because both metal balls fall the same distance, H, and release the same amount of energy.

When the velocity of the two metal balls is actually measured, guess what? Their velocities are exactly the same.

It looks like Galileo might be right: what determines how much energy we put into an object is how high we lift the object off the ground. And indeed, no matter how long Galileo made his U shaped track, the marble always had enough energy to reach its original height.

Slide 8: Drawing conclusions

Now for the final test of his hypothesis. Galileo made the long end of the track completely flat. What happened to the marble? It never stopped rolling. That kind of makes sense. We put energy into the marble by lifting it to the top of the track, but by making the track completely flat, we never gave the marble a chance to use the energy to climb back up to its original height. What conclusion do you draw from this?

The energy we put into the marble never went away. Unless it's actually used, energy remains there waiting to be used. The scientific way to say this is that energy is never destroyed; it may be converted into different forms of energy, or it may just sit there in storage, but energy is always conserved in one form or another.

What are some examples of one form of energy being converted into another form of energy?

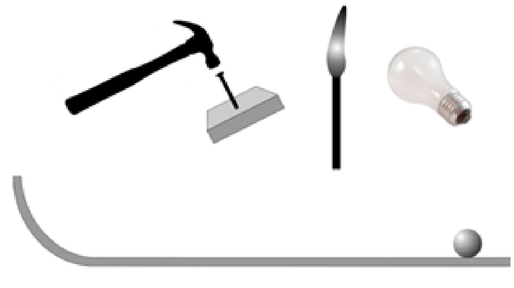
How about rapidly pounding a nail? Part of the mechanical energy you put into pounding the nail is converted into heating up the nail.

How about lighting a match? Stored up chemical energy in the match head is converted to heat and light, both forms of energy.

A light bulb converts electrical energy into the energy of heat and light.

What other conclusion can we draw from Galileo's rolling marble experiment? Let's think about the experiment again. When the marble was first released, the force of gravity made the marble roll down the track.

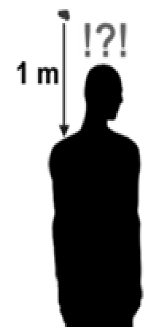
Here's my question. Was the speed of the marble the same when it first started rolling down the track as it was when it reached the bottom of the track?



Energy is never destroyed.

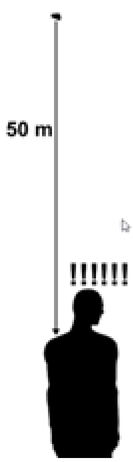
The marble rolls so fast that our eyes can't measure its speed as it rolls down the track, so let me ask you another question.

Slide 9: Graphing for understanding



Suppose someone dropped a small rock from one meter above you and it landed on your shoulder. A meter is about the height of a doorknob off the floor.

Now they do the same thing from a window 50 meters above your shoulder.



Which hurts more? Why? It's the same rock. Why did the falling rock hurt more when dropped from 50 meters?

Because the rock dropped from 50 meters is moving faster than the one dropped from 1 meter.

Let's see if we can graph this out.

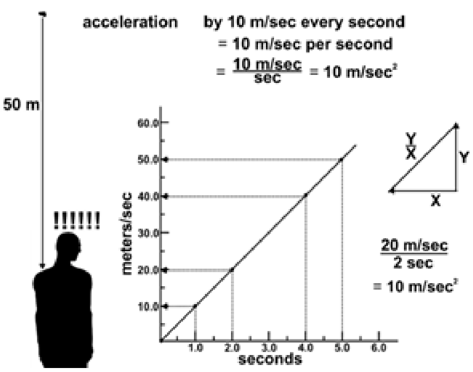
Along the X axis is time, in seconds, and along the Y axis is velocity of the rock, in meters per second.

Before we release the rock, the rock is not moving. At the moment we release the rock, the time along the X axis is zero seconds. And since the rock is not moving, the graph line starts out at the zero point for both the X and Y axes.
In the first second, which means we have to move over the number 1 on the X axis, how fast is the rock falling? We'll have guess, say, 10 meters per second.
By the end of the second second, how fast is the rock moving?
We said that the reason the rock hurt more when dropped from a greater height is that is by the time it strikes your shoulder, it's moving faster. In other words, the rock is picking up speed as it falls.

So if the rock is moving at 10 meters per second in the first second, how fast will it be moving at the end of the second second?

Well it's got to be faster than the 10 meters per second, because it's picking up speed as it falls. How about we say it's falling twice as fast? So if the rock is falling 10 meters per second after the first second, we're gonna say it's falling at 20 meters per second by the second second.

If we extend the graph line, how fast will the rock be falling at the end of four seconds?



Sure. 40 meters per second.

And at the end of 5 seconds, 50 meters per second.

What do you call it when something speeds up?

Acceleration.

As our rock falls, it's accelerating. By how much? How much faster does the rock fall each second?

The graph says that at 1 second, the rock is falling at 10 meters per second, and at the end of 2 seconds, it's traveling at 20 meters per second. In 1 second, it increased its speed by 10 meters per second.

Let's see if that increase in speed is the same between, say, 4 and 5 seconds. At 4 seconds, the rock is falling at 40 meters per second, and at the end of 5 seconds it's traveling at 50 meters per second. That's a 10 meters per second difference in 1 second, the same as before.

What units do you use to describe acceleration? How do you say that something is accelerating by 10 meters per second every second?

Instead of saying something is accelerating by 10 meters per second every second, you say, it is accelerating at 10 meters per second, per second. 10 meters per second per second is 10 meters per second squared.

An acceleration of 10 meters per second per second means that the speed is increasing at a rate of 10 meters per second every second.

How do you represent rate of change on a graph?

You look at the graph line. The graph line tells you how many units the Y axis increases for every one unit along the X axis. In this case, the speed of the falling rock increases by 10 meters per second every second, or 10 meters per second squared.

In other words, rate of change is the slope of the graph line: Y over X. Y over X is the number of units along the Y axis divided by the number of units along the X axis.

So long as that graph line is straight with no change in direction, it makes no difference how many units you use to calculate Y over X. The rate of change, in other words, the acceleration, will still be the same.

So you can start out with 3 seconds along the X axis, or 10 meters per second along the Y axis, when you're done dividing Y by X, X always ends up being 1 and Y will always be the same number of Y units per 1 unit of X.

For example, if you prefer to measure the rock's speed between 2 seconds and four seconds, the graph tells you that its speed rose from 20 meters per second to 40 meters second, a rise of 20 meters per second in those 2 seconds.
Its acceleration was 20 per second divided by 2 seconds, or 10 meters per second per second, the same acceleration it had between zero and 1 second. The rock's acceleration is constant.

Slide 10: Why should a rock falling from 50 feet be moving faster than one dropped from 5 feet?

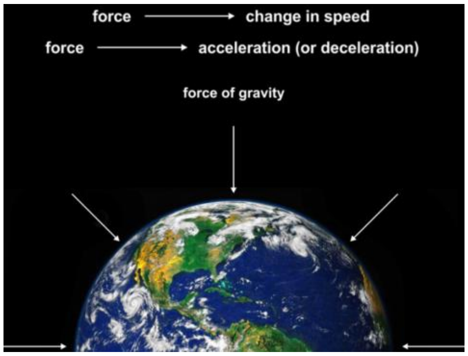
Why should a rock falling from 50 feet be moving faster than one dropped from 5 feet?

And why should the marble slow down as it tries to climb the other side of the track?

Why does the speed of a rock or a marble increase as they fall or roll toward the earth and slows down as they move away from the earth?

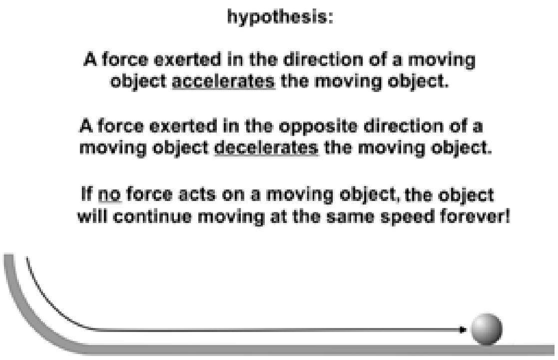
What is the one thing that a falling rock and a marble rolling down and then up a track are both experiencing?

The force of gravity. So what's our hypothesis?



Our hypothesis is that if an object experiences a force, its speed will change. What do we call a change in speed? Acceleration, if the speed increases, or deceleration if the speed decreases.

Slide 11: Hypothesis: a moving object experiences force.



So our hypothesis is that if a moving object experiences a force, it will accelerate when the force is with the direction of movement, and decelerate when the force is against the direction of movement.

That certainly makes sense, but what if the object is moving in a straight line and no force acts on the moving object? What happens to the speed of the moving object then? What does the hypothesis predict?

The hypothesis predicts that a force will change the speed of a moving object. No force, no change. A moving object with no force acting on it should continue on at its present speed.

For how long? Forever.

What kind of experiment could we design that shows a moving object with no force acting on it?

Why don't we just ask Galileo? He already did it with his rolling marbles. When he flattened out one side of the track, and released the marble, the force of gravity did make the marble roll down the track, but once the marble reached the bottom of the track and started moving horizontally, the force of gravity was now perpendicular to the direction of movement. With the force of gravity no longer acting with or against the direction of movement, the marble rolls as if it has no force acting on it at all, and just keeps on rolling.

Galileo's experiment four hundred years ago supports our hypothesis that once a force gets something moving in a straight line and the force is then removed, the object will continue at the same speed forever.

Slide 12: 3 things we know so far

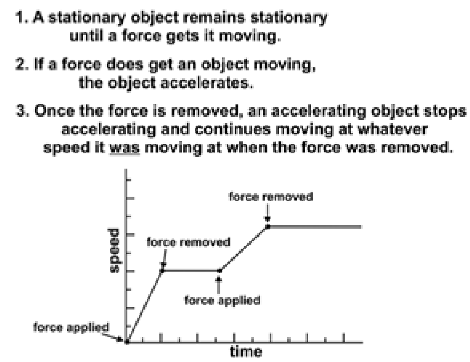
So, what have we got so far? Three things.

First, a stationary object remains stationary until a force gets it moving.

Second, if a force does get an object moving, the object accelerates.

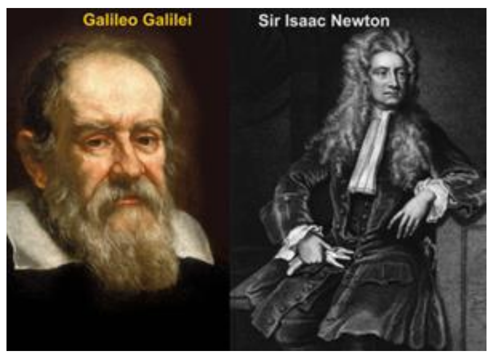
Third, once the force is removed, an accelerating object stops accelerating and continues moving at whatever speed it was moving at when the force was removed.

Here is a graph of these three ideas.



Slide 13: Who is Isaac Newton?

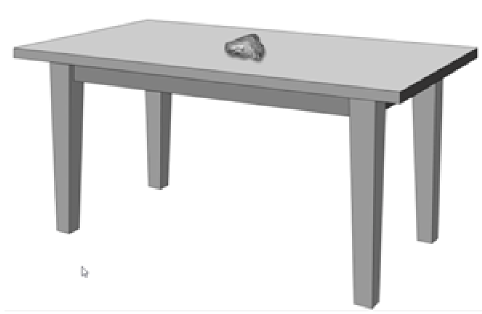
The year Galileo died, Isaac Newton was born. Newton picked up on Galileo's experiments and agreed with these three ideas, but then he did something very important. He developed mathematical equations for moving objects. Because Newton's mathematical equations predicted the movement of the planets and the stars, people quickly realized that heavenly bodies obeyed the same rules as objects on earth. To say that heaven was governed by the same rules as lowly earth was a pretty radical idea in those years.



Besides developing the mathematically formulas explaining the movement of bodies, Newton also created a whole branch of mathematics called calculus, and even performed experiments that explained a lot of things about light.
He was so important to development of science and mathematics that in 1705 Queen Anne, the Queen of England, knighted him for his scientific accomplishments, and we now call Isaac Newton, Sir Isaac Newton.

Slide 14: Force of gravity

Here is a stationary rock sitting on a table, being acted on by the force of gravity. We just got done saying that a stationary object acted on by a force accelerates until the force is removed, but this rock is not moving. Why not?



Because the downward force of gravity is being opposed by an equal upward force exerted by the table.

If I put a heavier rock on the table, the table now exerts a stronger force.

How does the table know how much force to apply?

Here's why Newton deserves to be called Sir Isaac Newton. Newton said that the reason the table exerts more upward force when a heavier object is placed on the table is that whenever one object exerts a force against another object, the other object reacts with an equally strong force in the opposite direction. Action, reaction.

Slide 15: When one object exerts a force on another object, the other objects pushes back with an equal force.

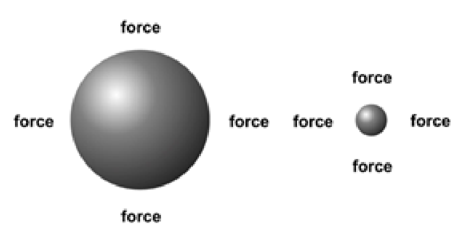
We actually see this all the time. When a rocket launches, the force pushing the hot gas out the tail of the rocket exerts an equal force in the opposite direction against the rocket, and lifts the rocket upward.

So let me ask you: do you think you can swim through space by thrusting your arms backward and creating an equally strong force that pushes your body forward?

No. Why not? Because Newton said you need two objects. When one object exerts a force on another object, the other objects pushes back with an equal force.

When you're sitting out there in outer space, there is no other object out there to push back at you. The rocket had the gas to push against. A rocket cannot simply flap its fins to get moving. It needs something to push against.

Slide 16: Forces always come in pairs.



What Newton was saying is this: a single body cannot exert a force. In order for there to be a force, there has to be another force, equal to the first force and opposite in direction. Simply put, forces always come in pairs, and they always oppose each other with an equal force.

The only way you know there a force is present is when another object is around to experience it. But since that other body also exerts a force, there is no such thing as a single force.

So, no matter how much the force of gravity pulls you down, just remember, you're exerting an equal force on the earth and pulling the earth toward you.

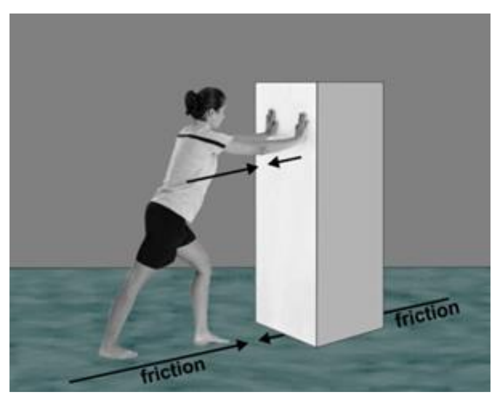
Slide 17: If every force is met with an equal and opposite force, how does anything ever move?

Does all this really make sense? If every force is met with an equal and opposite force, how does anything ever move?

When you push against this box, the box does push against you with an equal force.

And if you were in outer space, the force you exerted against the box would move the box backward, while the force the box exerted against you would send you backward.

It's a different situation on earth, because we're not talking about just you and the box. To move the box, yes, you are using your muscles, but your feet are pushing against the floor and the floor is pushing back and combining with your muscles against the opposing force of the box and force of friction of the box against the floor.

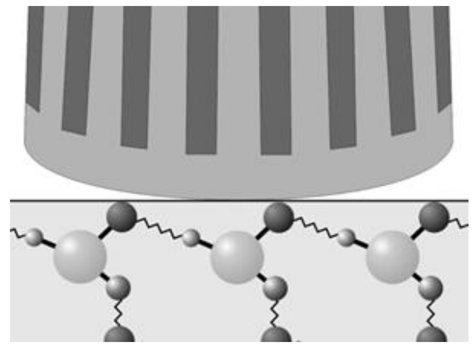


In order to get the box moving, your muscular force and your force of friction have to exceed the opposing force of the box and its force of friction.

Slide 18: What is the force of friction?

What is the force of friction?

The force of friction is a chemical force. When you place a lamp on a table, the reason the lamp does move the table is that chemical bonds between the atoms and molecules within the table are pushing upward with a force equal to the weight of the lamp.

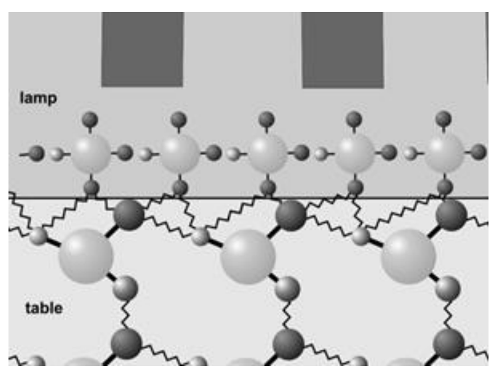


The lamp will rest on the table top without moving until the weight of the lamp exceeds the upward strength of the chemical bonds.

Slide 19: It takes less force to keep an object moving than it does to get it moving.

Have you ever noticed when trying to move something that when you finally do get it moving, it takes less force to keep it moving than it did to get it moving?

That happens because once whatever you're moving starts moving, the force of friction suddenly drops. Why?
For this lamp sitting on a table, the force of friction is generated by the chemical bonds that develop between the molecules in the lamp and the molecules in the table.



When the box starts to move, the bonds break and with the lamp moving along the table top, it becomes difficult for the molecules in the table to reattach to the moving molecules in the lamp.

Slide 20: Force

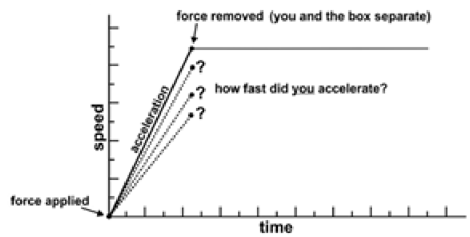
We said that if you push away a box in outer space, the box moves in one direction, while the force of the box pushes you backward, in the opposite direction.

How long will you and the box continue to travel in opposite directions?

Forever, until you or the box enters the gravitational field of some star or planet, or is struck by a comet.

Will you and the box be traveling at the same speed?

Slide 21: We can use graphs to answer questions.



Maybe if we graph it out, we can answer these questions.

Let's start with the box. Time is measured along the X axis, and speed along the Y axis.

The box begins at rest, with zero speed.

When the force is applied, and the box begins to move, what happens to its speed?
It continues to increase until you and the box separate and no further force is applied.

After that, the box continues at the same speed until it reaches the end if the frictionless ice rink.

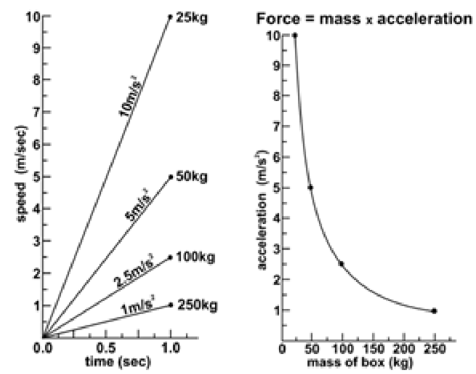
The rate of acceleration is simply the Y axis over the X axis: the increase in speed per unit of time.

What about you?

When you exerted a force against the box, the box exerted an equal force against you. So you also accelerated from a stationary position. Since the same amount of force that accelerated the box was also directed at you, did you accelerate at the same rate as the box?

We know that you stopped accelerating at the same time that the box stopped accelerating, but how fast were you going when you and the box separated?

Slide 22: Finding the answers



One way to answer this question is to measure your speed and the box's speed as you push the box away.

Suppose you and the box each weigh 100 kg. You push the box with enough force that after 1 second, the box slides 2.5 meters. What is its speed after that 1 second? 2.5meters per second.

What is its acceleration?

Since it went from zero to 2.5 meters per second in 1 second, its acceleration is 2.5 meters per second squared. What was your acceleration?
Since the box exerted the same force on you that you exerted on the box, your acceleration is also 2.5 meters per second squared.

Suppose we now exert the same force to push different weight boxes. Here's what we find. Pushing a 250 kg box causes it to accelerate away from you at 1 meter per second squared. A 50 kg box accelerates away at 5 meters per second squared. An even lighter 25 kg box accelerates at 10 meters per second squared.

Does your acceleration change when you push different weight boxes?

No, because you're pushing each box with the same force, and therefore each box is pushing back at you with the same force.

Looking at this graph, do you see any relation between mass and acceleration?
It sure looks like the more mass, the less the acceleration. What's a better way of graphing the relation between mass and acceleration?
Sure, make the X axis mass and the Y axis acceleration.

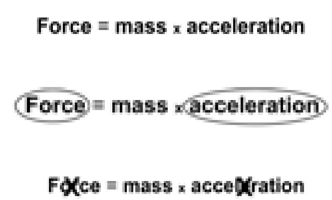
For a 250 kg box, the acceleration is 1 meter per second squared.

For a 100 kg box, the acceleration is 2.5 meters per second squared.

For a 50 kg box, the acceleration is 5 meters per second squared.

And for a 25 kg box, the acceleration is 10 meters per second squared.
This graph shows that when the same force is exerted against objects of different mass, the more mass the object has, the less it accelerates. Sir Isaac Newton summarized this in his famous formula, force equals mass times acceleration.
For Newton, mass was a measure of how much an object resists being accelerated.

Slide 23: What conclusion can you draw?

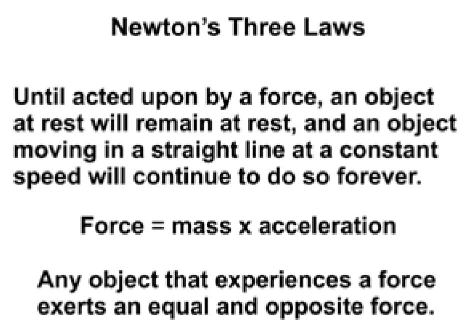


What conclusion can you draw when you see an object accelerating? According to force equals mass times acceleration, if something is accelerating, there must be a force acting on the object to make it accelerate.

Conversely, if an object is moving at a constant speed, or not moving at all, any force that is acting on the object is being offset by an equal and opposite force, and there is no net force.

Force equals mass times acceleration also tells you that if there is no net force acting on a mass, there is no acceleration. A stationary object will remain stationary, and a moving object will continue moving at the same speed until a force does act on it and cause it to accelerate or decelerate.

Force equals mass times acceleration is why a space walker cannot swim through space. He or she can move their arms and legs all they wants, but without something else around to exert an opposite and equal force, there is no force and therefore, according to the formula force equals mass times acceleration, no acceleration.



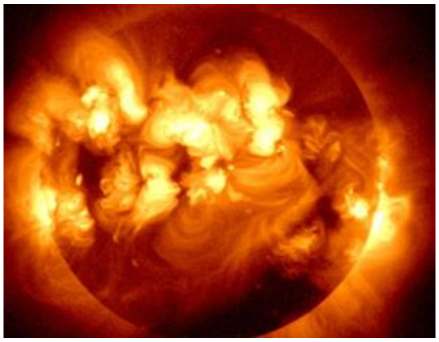
Here, then, are Newton's three laws.

Until acted upon by a force, an object at rest will remain at rest, and an object moving in a straight line at a constant speed will continue to do so forever.

Force equals mass times acceleration. Any object that does experience a force exerts an equal and opposite force.

Slide 24: Ask questions.

I think you now have a good understanding of the scientific method and the powers of observation.



From now on I want to listen when you hear something, and really see things when you look at them.


I also want this introduction to science to make you realize that science is the art of looking at something and asking why that happens, or better yet, why something else didn't happen.

Chemistry, biology, and physics are all around you, and an understanding of these subjects will allow to understand your world and provide you with ways to make your world, our world, a better place to live.