ENGINEERING PATHWAYS

PHYSICS HANDBOOK

"You have to make rules, not follow them."

-Sir Isaac Newton

The Engineering Pathways Learning Kit

INTRODUCTION

Rube Goldberg Machines, what are they? The best thing to do would probably go on YouTube and watch some videos of them. What you'll see is many different, seemingly unrelated objects, working together in a long series. They last from a few seconds to many minutes long and generally end with doing a simple task, like pouring lemonade!

Now that you have this kit, we will lay out exactly what this kit is about, how to get the most value out of it, and what makes it so unique. But first, who are we?

We are two recent mechanical engineering graduates from Iowa State University who grew up building Rube Goldberg machines. We developed a lifelong passion for physics, math, and engineering from our experiences as children. We want this kit to introduce more kids to the wonderful world of science, and hopefully educate and inspire them to pursue a career in a STEM field and follow in our footsteps.

ABOUT THE KIT

Rube Goldberg machines demonstrate many different concepts of physics. We engineered our own parts and developed a booklet that work together to facilitate learning and guarantee a lot of fun! The booklet contains many lessons that build upon the parts included in the kit. This Rube Goldberg machine kit is perfect for introducing and reinforcing a basic understanding of physics as well as providing many hours of fun and creativity.

The kit can be approached from two perspectives. 7th-12th grade and below 7th. This booklet has two sections, one developed for each age range. The difference is the complexity of the writing and concepts. Feel free to use both resources though!

ENGINEERING PATHWAYS – A RUBE GOLDBERG KIT CONTENTS

12" Hot Wheels Track

8" Hot Wheels Track

Hot Wheels Track Connectors

Hot Wheels Car

Pulleys

Lever and Fulcrum

Our Custom 3-D Printed Bucket

Our Custom 3-D Printed Inclined Plane

Slinky

Ping Pong Balls

Popsicle Sticks

String

Plastic Cups

Balloons

Various Size Rubber Bands

Wooden Blocks – Dominos

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Construction Paper Multiple Colors

Optional Due to Safety Concerns:

Mouse Traps

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A BRIEF INTRODUCTION

In 1928, cartoonist Rube Goldberg's sketches of complicated machines that performed simple tasks became world renown. His name soon began to embody this very concept. Today, people all over the world build Rube Goldberg Machines and compete in competitions run by top universities. As the creators of this Rube Goldberg Machine kit, we want to inspire young people around the world to become interested in science and someday even pursue a career in a STEM field!

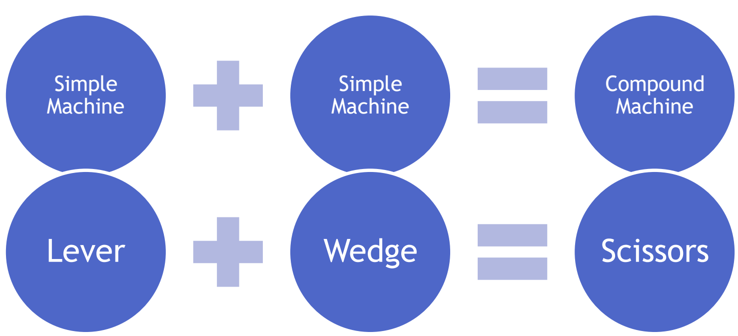
Rube Goldberg machines are not only educational, but fun! You will use your creativity, ingenuity, and resourcefulness in order to build a huge complex machine connected with smaller and simpler components. You will learn about physics while just building a machine, and if you want a deeper understanding, this booklet will explore each component included in the kit and demonstrate how they are little science experiments. For example, a Hot Wheels car going around a loop-the-loop demonstrates centripetal force. What's the minimum speed a Hot Wheel needs to go to successfully go around the loop?

PHYSICS – AN INTRODUCTION

In this section of the booklet, we will be discussing many things related to physics. We will take components that are in your kit and show you how they are little physics experiments! We love physics because it can explain the motion of everything around us. We can use physics to calculate how far you can throw a baseball, or the minimum speed a car must go to successfully traverse a loop-the-loop, or even calculate how fast a spaceship needs to go to escape earth's gravitational pull. We have one goal with this Rube Goldberg machine kit, we want to pass our passion for physics and engineering on to you, and maybe one day you will become engineers like us.

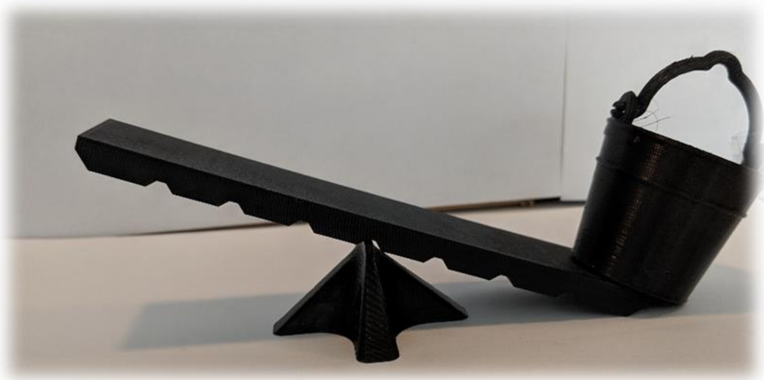
SIMPLE MACHINES

A simple machine is a mechanical device that changes the magnitude or direction of a force. They are used primarily because they give us mechanical advantage. Mechanical advantage is the amount that the input force is multiplied by the machine. What does this mean? Simple machines make doing work easier. There are six types of simple machines: lever, pulley, inclined plane, screw, wedge, wheel and axle. These simple machines can be combined in order to form compound machines.



Effort force is the force that is input by the user of the simple machine. The effort distance is simply the distance over which the input force is used. The resistance is the work done on the object you are trying to move.

$$Effort\ Force\ x\ Effort\ Distance = Resistance\ Force\ x\ Resistance\ Distance$$



The Ideal mechanical advantage of a simple machine is the ratio between the distances. This calculation assumes that there is no friction present. In reality, mechanical advantage is limited by friction forces.

$$IMA = \frac{Effort\ Distance}{Resistance\ Distance}$$

The actual mechanical advantage is the ratio of the forces.

$$AMA = \frac{Resistance\ Force}{Effort\ Force}$$

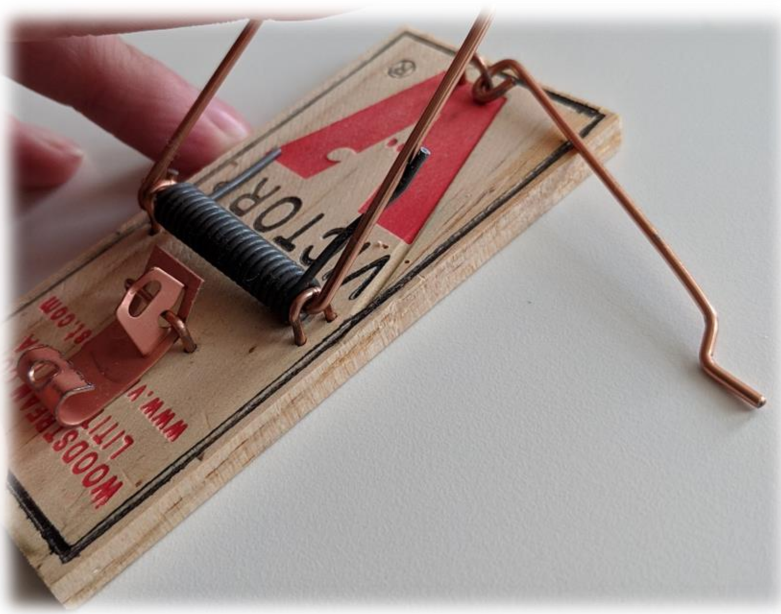
Sources:

https://www.ck12.org/physics/simple-machines-1501903848.65/lesson/Simple-Machines-PHYS/

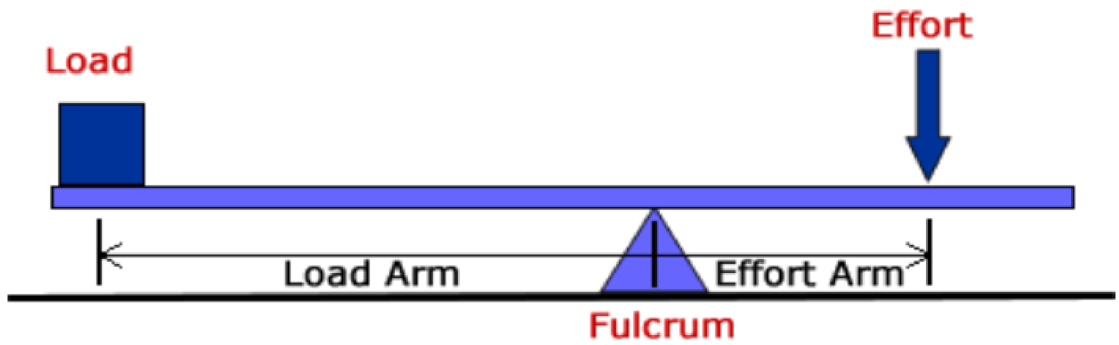
LEVERS

A mousetrap is a simple, but ingenious device. When a mouse trap is set, the spring is compressed. When the spring is compressed potential energy is stored. When the trap is released the potential energy that is stored in the spring is converted into kinetic energy, propelling the arm of the trap forward.

A mousetrap is also an example of a simple machine called a lever. A mousetrap is an example of a class 2 lever because the load moves in the same direction as the effort. In this example, the spring in the mousetrap is acting as the effort, and the load is the swinging lever.

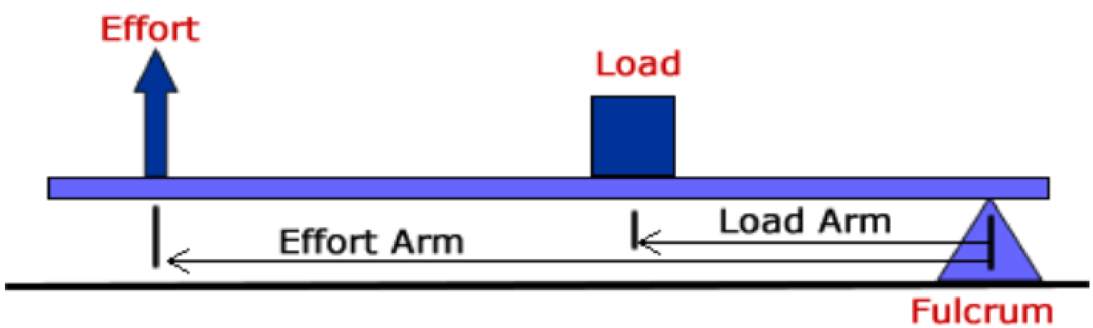


This photo shows a bucket balanced on a lever. Both are included in your kit!



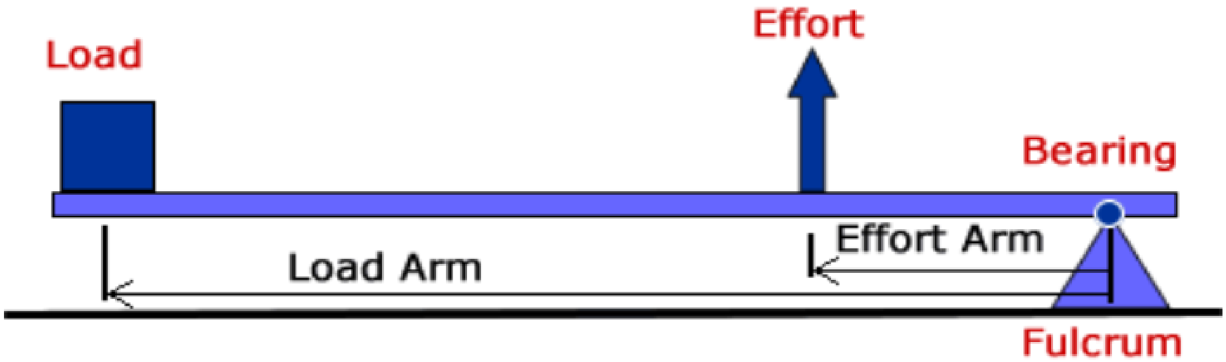
Class 1 lever

A class 1 lever features a fulcrum that is located between the load and the effort. The length of the effort arm can be less than, equal to, or greater than the load arm length.



Class 2 lever

The load in a class 2 lever moves in the same direction as the effort. The load is between the effort and the fulcrum.



Class 3 lever

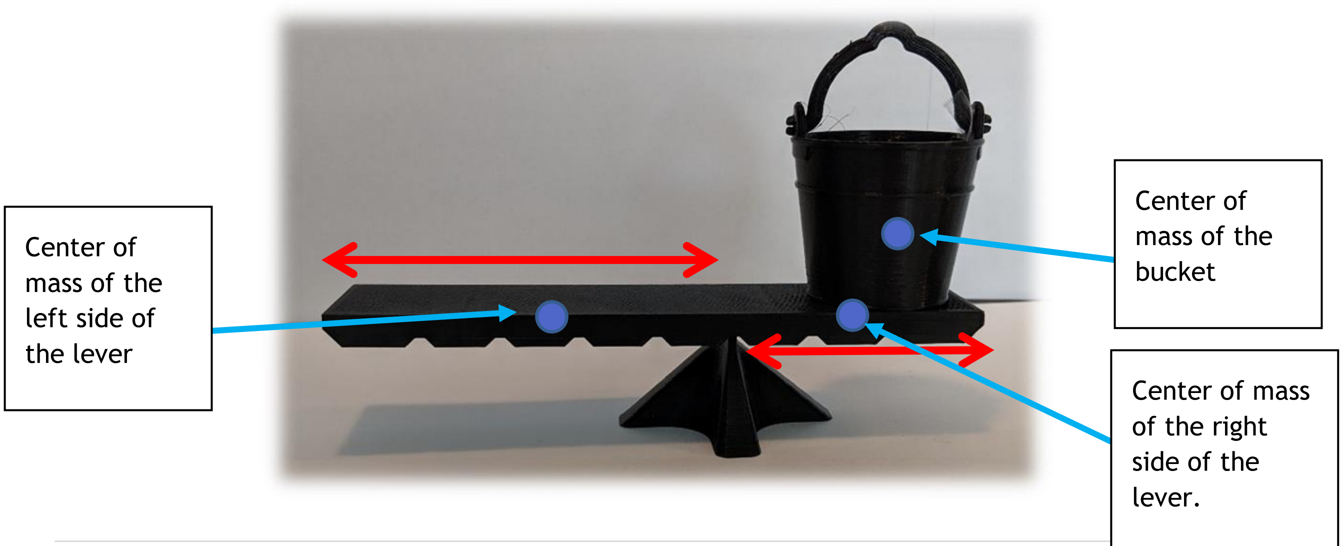
In a class 3 lever the load moves in the same direction as the effort. The effort is in between the fulcrum and the load.

According to these three diagrams of levers, which one do you think can lift the heaviest load with the smallest effort?

Sources:

https://learning-center.homesciencetools.com/article/mousetrap-physics/

MOMENTS OF A LEVER (ENGINEERING STATICS)



What is a center of mass?

A center of mass is an imaginary point in a body of matter where, for convenience in certain calculations, the total weight of the body may be thought to be concentrated (Encyclopedia Britannica). That means that we can take an object, in this case the bucket, and perform our calculations as if the bucket was that point. This works because if you average the bucket on each side, the average mass of the bucket will be in the center.

We will also use the center of mass of each side of the lever, because if you average the mass of each side, the total effect will be at the center of mass.

Newton's Second Law

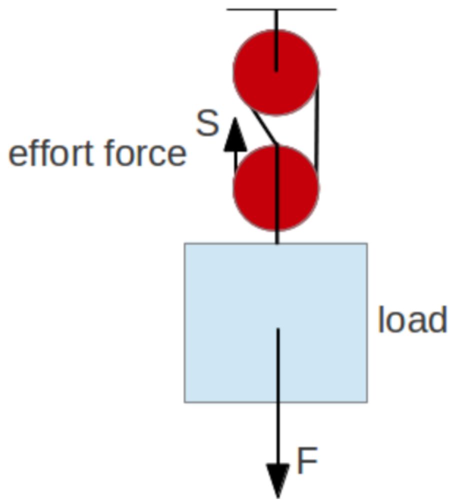
Next, we will consult Newton's Second Law of Motion. This law states that force is equal to mass x acceleration (F=ma). This means that if we add up every force that is acting on a system, it will be equal to the acceleration of the system times it's mass. Since there is no acceleration in this problem, a = 0. If a = 0, then F = 0 as well.

Weird, right? Now, our equation tells us that our force equals 0. How is that useful? Well, just because all of the forces on this system together are equal to zero, the individual forces are not. We know, however, that the individual forces must add up to 0. This process of called Statics. Statics is a subdivision of mechanics, and all part of physics. First and second year students in mechanical engineering always take a whole class on Statics.

Solving for the forces

Newton's Second law told us that all of the forces acting on this system, must equal 0, but how do we prove that? We must calculate these individual forces, add them up, and hope they equal 0. (They will).

PULLEYS

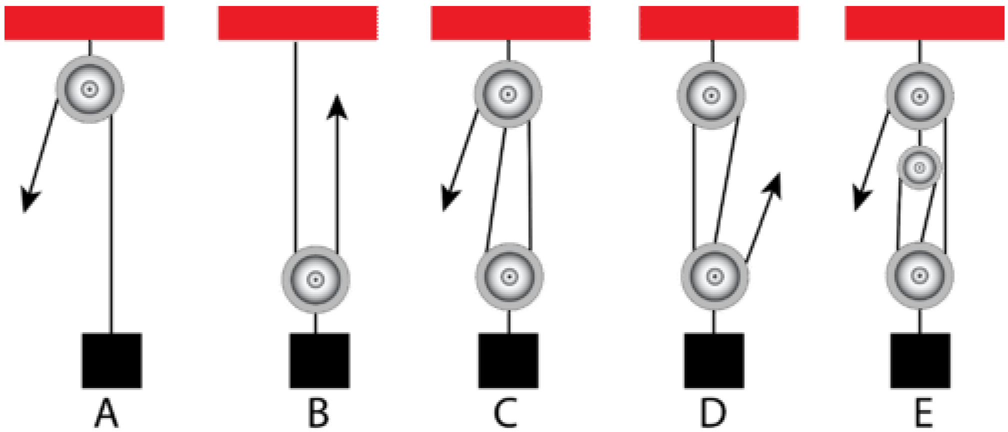


S=⅓ F

Sometimes it isn't possible to lift an object with the force that a human can generate. In this case, a simple machine like a pulley can be beneficial. A basic pulley is comprised of a wheel on a fixed axle with a groove along the edges to guide a cable. When pulleys are combined you can make lifting heavy objects much easier! As more pulleys are added you increase your mechanical advantage and lifting the same load becomes increasingly easy. The tradeoff is that as you increase the number of pulleys you also require a greater length of rope.

This photo shows a 3-d printed pulley with ball bearings to help it rotate smoothly. Three of these pulleys are included in your kit!

The IMA of a pulley system can be determined by counting the number of supporting strands of a rope in the system. Be careful though, because in some systems the rope to which the effort is applied will be a supporting strand.



In figure A the rope to which the load is being applied is not a supporting strand. However, in figure B the rope to which the load is being applied is a supporting strand. It helps to draw free body diagrams when working with pulleys to understand how forces are being distributed through the cable network.

$$S = \frac{F}{\mu * n} = \frac{mg}{\mu * n}$$

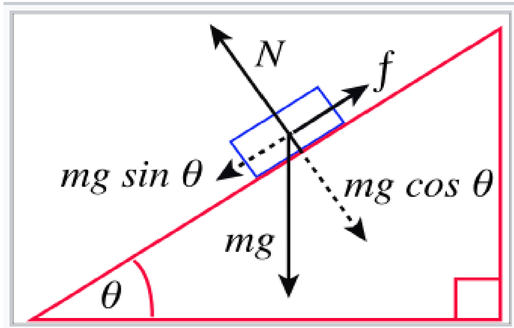
$$S = effort\ force$$

$$F = Load\ (what\ you\ are\ lifting)$$

$$m = mass$$

$$\mu = friction\ coefficient, between\ 0\ and\ 1$$

$$n = number\ of\ ropes\ betweeen\ the\ pulleys$$



$F_{friction} = \mu * F_n$

μ = friction coefficient

F_n= normal force

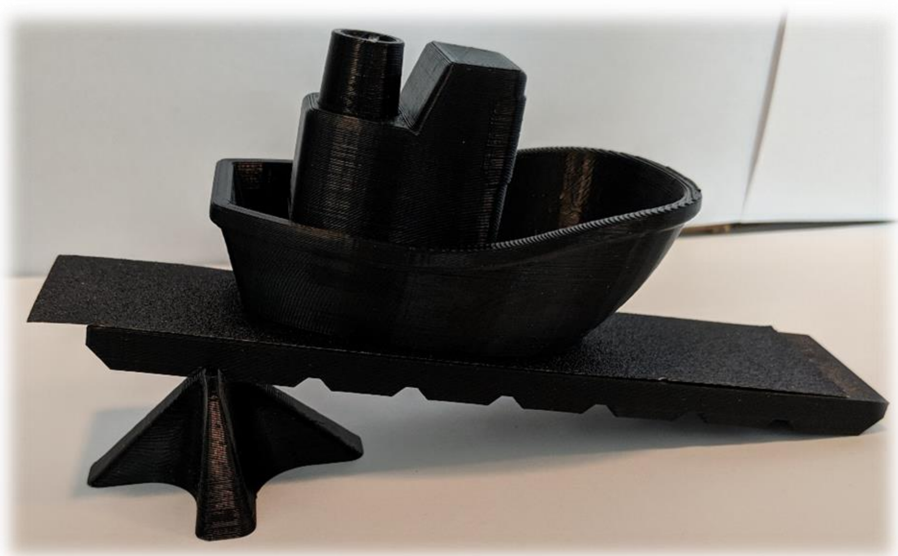
Why does a ball running down a ramp accelerate faster if you increase the steepness of the ramp?

When solving inclined plane problems start by identifying the amount of force directed straight down due to gravity. This force can then be broken into components, one parallel to the surface of the plane and one perpendicular to the surface of the plane. The parallel component of the force that pulls the object down the ramp is equal to $mg * \sin(\theta)$. As the steepness of the ramp increases (increasing the angle theta) the force value increases. Using the equation $F = m * a$ we can see why the object would accelerate faster as the angle increases.

$F_{parallel} = mg * \sin(\theta)$	$m = mass$ $g = gravitional\ constant$
$F = m * a$	$a = acceleration$

In your kit we included an inclined plane and sandpaper where you can see how all this works! Feel free to do the experiment below on your own.

With no added friction from the sand paper on the inclined plane, the toy boat slides down. The downward force of gravity on the boat is great enough to overcome the friction between the inclined plane and the boat. What do you think happens if we put sandpaper on the inclined plane?



When the sand paper is added to the inclined place, the boat doesn't move! This is because the friction force exerted on the boat from the sand paper is greater than the downward force of gravity on the boat.

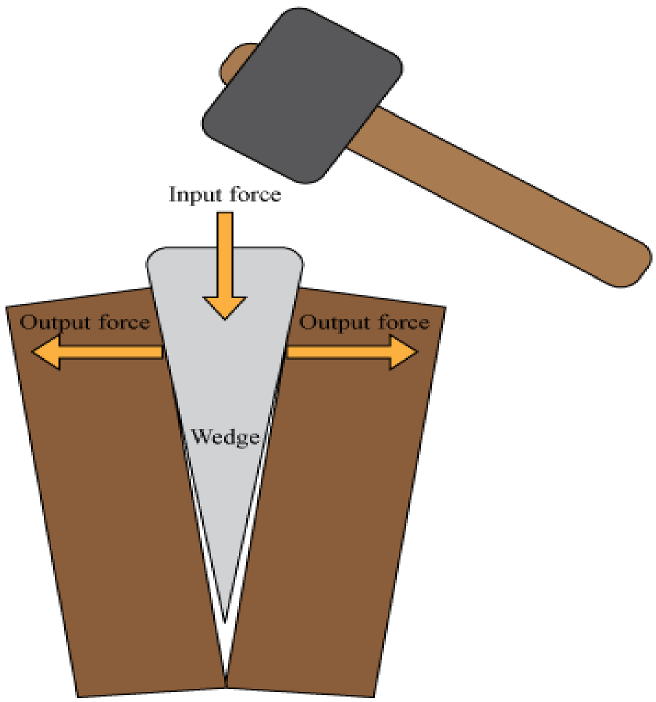
We cut out a small rectangle of sand paper that fits the inclined plane.

Are there any other uses for an inclined plane?

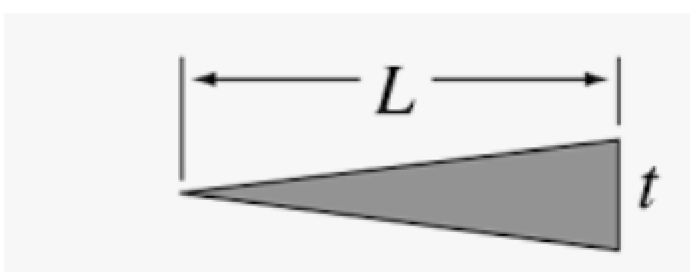
Inclined planes can be used to lift an object over a distance. This is useful because the component of the object weight acting parallel to the plane is less than the total weight. If we push or pull the object parallel to the plane, we can move the object with less effort than if we lifted the object straight up.

$$IMA = \frac{Effort\ Distance}{Resitance\ Distance} = \frac{Length}{Vertical\ Height} = \frac{1}{\sin{(\theta)}}$$

WEDGE



A wedge is simply two inclined planes back to back. A wedge can be used to cut or split objects apart. The input force is applied to the large end of the wedge and the wedge applies this force along both of its sloping sides. An example of a wedge is a simple kitchen knife. A wedge applies more force to the object than the user applies to the wedge. A longer, thinner wedge has a greater mechanical advantage than a shorter, wider wedge.



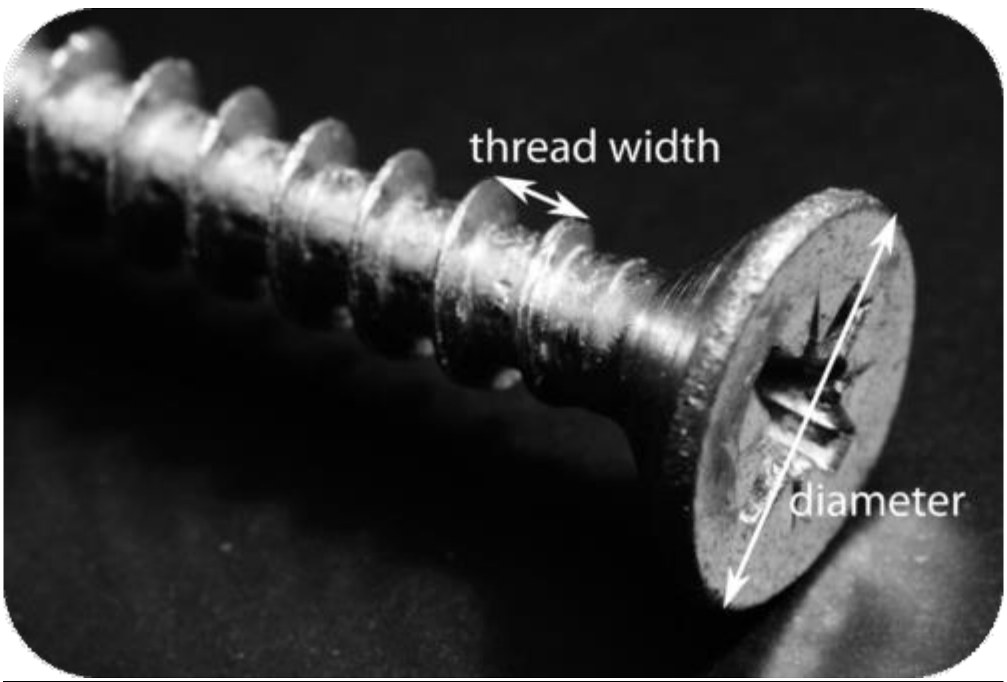
$$IMA = \frac{L}{t}$$

SCREW

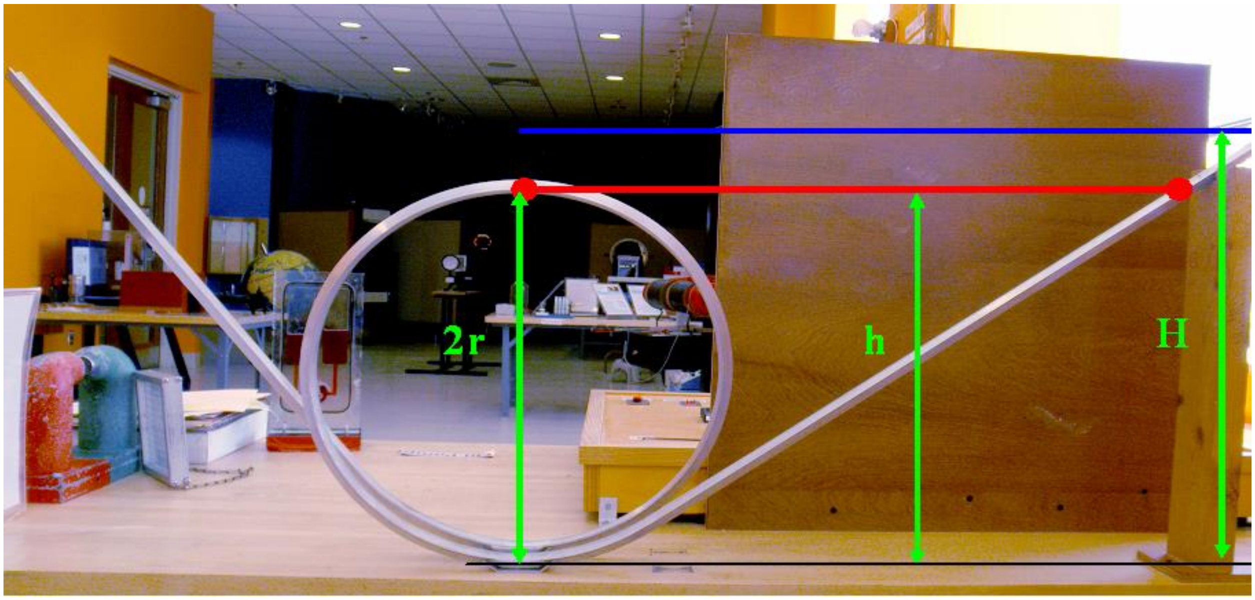
A screw is simply an inclined plane wrapped around a cylinder. The mechanical advantage of a screw increases as the density of the threads increases. The ideal mechanical advantage of a screw is simply the circumference of the screw head divided by the thread width.

IMA=effort distance/resistance distance= circumference of screw head/thread width

$$IMA = \frac{Effort\ Distance}{Resistance\ Distance} = \frac{Circumference\ of\ Screw\ Head}{Thread\ Width}$$



LOOP DE LOOP



A loop de loop is a perfect tool to illustrate the phenomena of work, potential energy, and kinetic energy. If we were to place a ball at a height, h on the track and release it would the ball make it around the loop the loop? No, the ball would not make it around the loop! However, if we place a ball at any point above height h then the ball will make it around the loop the loop.

$$PE = mgh$$
$$KE = \frac{1}{2}m * v^2$$
$$W = PE_{intitial} = PE_{final} + KE_{final}$$

$$PE = potential\ energy$$
$$KE = Kinetic\ energy$$
$$v = velocity$$
$$W = work$$

What is happening?

<u>Beginning</u>

When you raise the ball, you are doing work on the ball. You increase the height of the ball off of the table and now it has a potential energy equal to the work you did on the ball. The greater the initial height of the ball the greater the initial potential energy of the ball. This is the only energy that the ball has to move down the track and around the loop. When you release the ball, it starts moving at some velocity and the potential energy is converted into kinetic energy.

<u>Middle</u>

Once the ball reaches the bottom of the loop all of the energy is in the form of kinetic energy because the height above the table is zero (PE=0). As soon as the ball passes this point, speed begins to decrease as kinetic energy is being converted back into potential energy. Due to the conservation of energy, we know that the amount of potential and kinetic energy is equal to the initial work done placing the ball on the ramp.

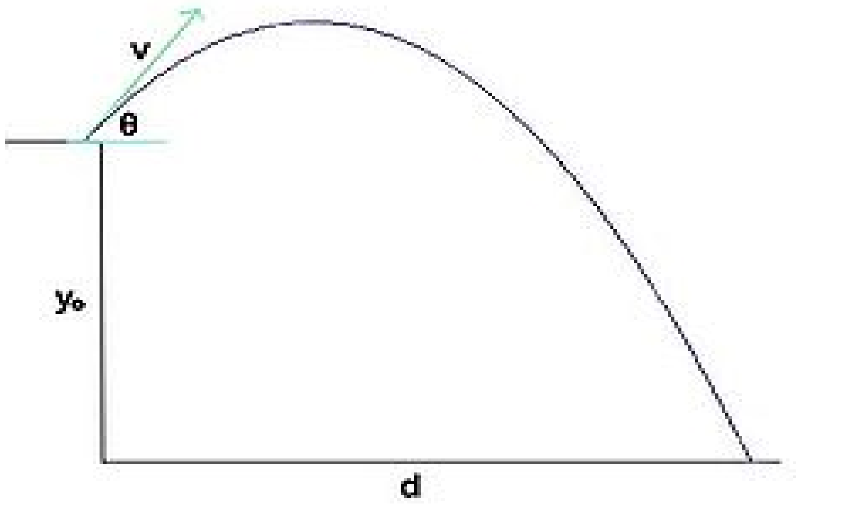
<u>End</u>

When the ball finally reaches the top point of the loop the loop, it needs to have enough kinetic energy to keep moving without falling off the loop. If we released the ball at height h on the track then the kinetic energy at this point would be close to zero. This is why the ball cannot make it around the loop at a height of h or less. However, when we place the ball above height h then the ball has plenty of kinetic energy at the top of the loop to traverse it. The amount of kinetic energy needed to keep the ball on the loop is equal to the amount of work done by the centripetal force.

$$Fc = m * \frac{v^2}{R}$$

$$F_c = centripetal\ force$$
$$v = tangential\ velocity$$
$$R = Radius\ of\ Circle$$

RANGE OF A PROJECTILE



$$d = \frac{v^2}{2g}(1 + \sqrt{1 + \frac{2g * y_0}{v^2 sin^2\theta}}$$

$$d = horizontal\ distance\ traveled\ by\ projectile$$
$$v = velocity$$
$$g = gravitational\ constant$$
$$\theta = angle\ projectile\ is\ launched\ at$$
Y_0=initial height of projectile

If the initial height, Yo is equal to zero (meaning the object is being launched on flat ground) the equation simplifies to:

$$d = \frac{v^2}{g}\sin(2\theta)$$

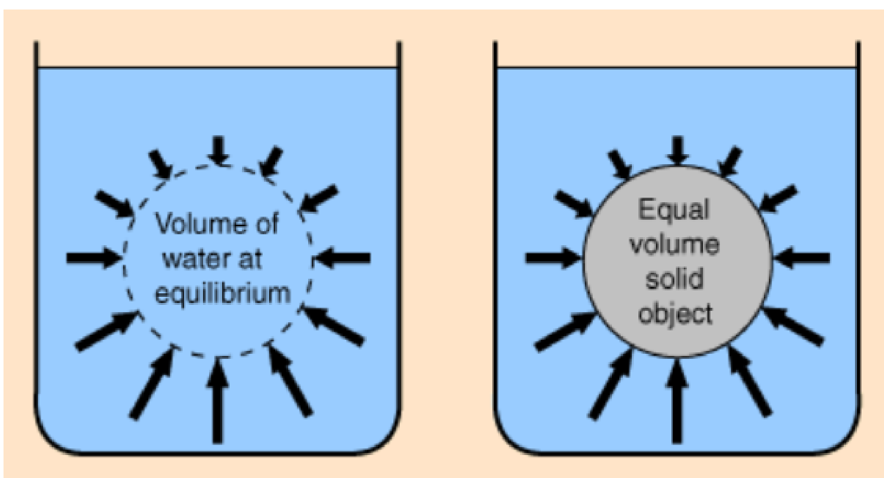
Sources:

http://www.phys.ufl.edu/~nakayama/lec2048.pdf

BUOYANCY

Here is a little toy boat floating in water. What makes it float? Buoyancy!

Buoyancy results from the fact that fluid pressure increases with depth and the pressure acts on the submerged object from all directions. This results in an unbalanced force on the bottom of the object because the bottom of the object is at a depth greater than the top of the object. The buoyancy force on the solid is equal to the weight of the water displaced. This is Archimedes' principle.



$$F_{bouyancy} = \rho g V$$

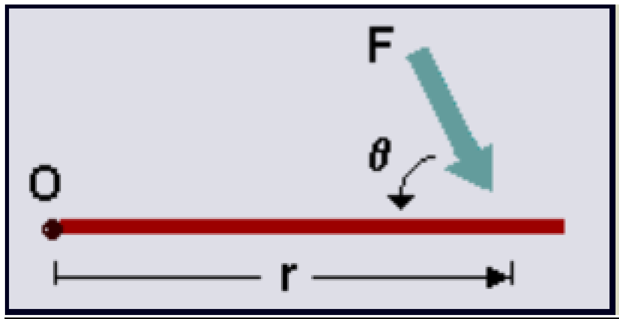
Where p is density of the fluid, g is equal to the gravitational constant, and V is the volume of water displaced by the object.

TORQUE

A torque is an influence which tends to change the rotational motion of an object. Another way to define torque is with the following equation

$$Torque = Force\ Applied * Lever\ Arm\ Length$$

The lever arm is the perpendicular distance from the axis of rotation to the line of action of the force. The maximum amount of torque occurs when the force is perpendicular to the lever arm.



In the case of the image above the torque would be calculated as follows:

$$Torque = r * F * \sin(\theta)$$

Sources:

https://www.physics.uoguelph.ca/tutorials/torque/Q.torque.intro.html

SPRING FORCE

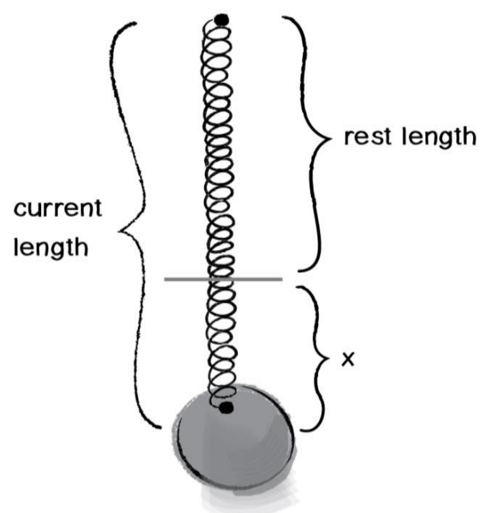
You know the slinky that's included in your kit? That's a spring! Here is a picture of the Slinky stretched out. If I let go of the Slinky what would happen? It would slam together! This is because Slinkys are springs, and the spring force will make the slinky move to its equilibrium position.

The equilibrium position is the spot that things will naturally go to. So in the case of the slinky, if it is stretched out, it is NOT in equilibrium. You can actually calculate how much force a spring can exert using the equation below!

$$F_{spring} = -k * x$$

K is the constant of the spring. This constant changes for every spring. If a spring is more stiff or less still, the k value will change.

X refers to the displacement of the spring. It is the difference between the rest length of the spring at equilibrium and the new length of the spring after it is stretched or compressed.



NEWTON'S LAWS OF MOTION

We will begin our discussion of physics with Isaac Newton's Three Laws of Motion. Back in 1687, Sir Isaac Newton of England published his Three Laws. These laws, in the form of equations, can describe the motion of objects in almost every circumstance. Newton's work helped spawn the age of classical mechanics.

First Law:

Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it.

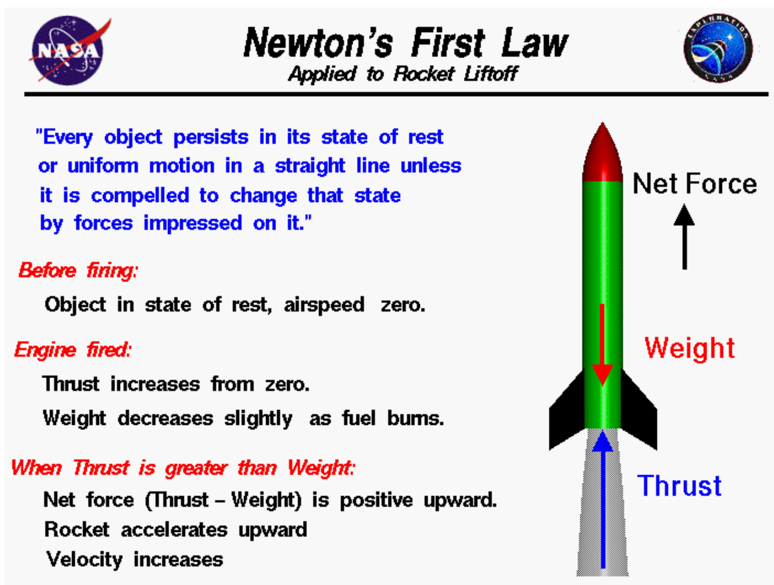


Figure 1: NASA Example (https://www.grc.nasa.gov/www/k-12/rocket/newton1r.html)

Second Law:

The relationship between an object's mass m, its acceleration a, and the applied force F is F=ma. Acceleration and force are vectors (as indicated by their symbols being displayed in slant bold font). In this law the direction of the force vector is the same as the direction of the acceleration vector.

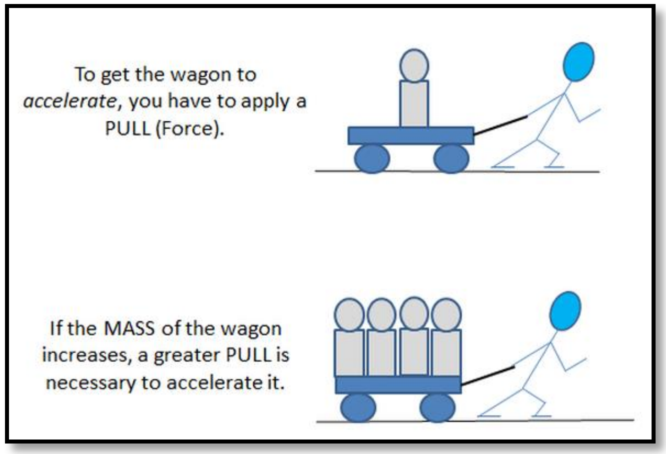


Figure 2: Example (http://physicalsciencetext.weebly.com/41-newtons-second-law-of-motion.html)

Third Law:

For every action there is an equal and opposite reaction.

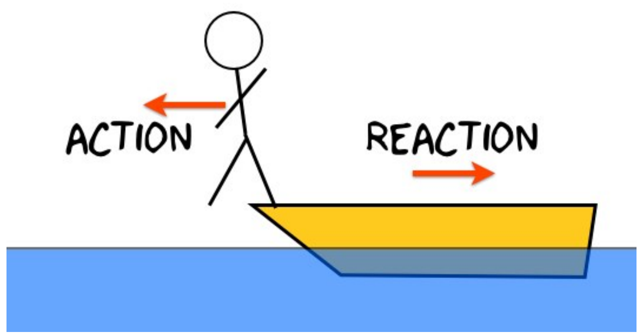


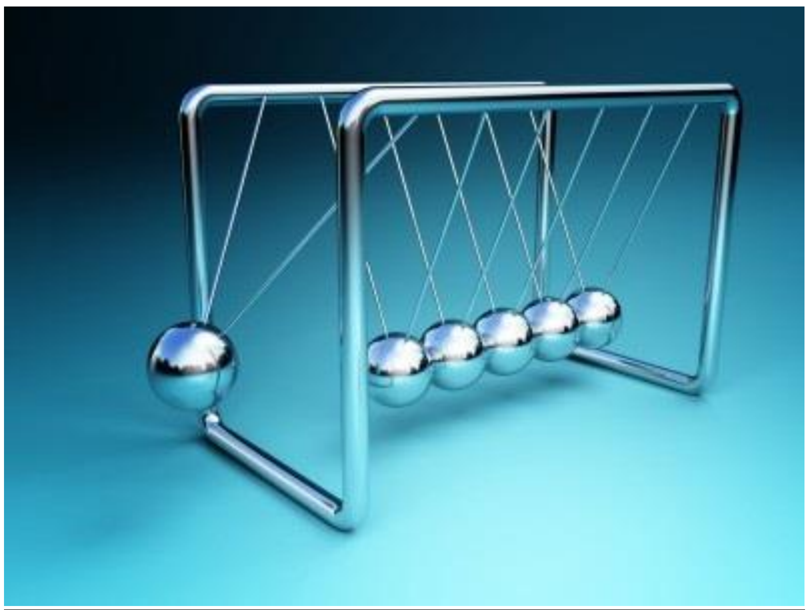
Figure 3: Example (https://www.wired.com/2013/10/a-closer-look-at-newtons-third-law/)

MOMENTUM

Momentum can be defined as “mass in motion”. All objects have mass and if an object is moving it also has momentum. The amount of momentum that an object has is dependent upon how much mass is moving and how fast it is moving. This is shown in the following equation:

$$Momentum = mass * velocity$$

The units for momentum are mass times velocity units. The standard metric units for momentum is kg*m/s.



PHYSICS OF COLLISIONS

Elastic Collision

Elastic collision is a collision in which there is no net loss in kinetic energy in the system from the collision. Both momentum and kinetic energy are conserved in elastic collisions.

Momentum is conserved as shown in the following equation.

$$m_A * V_{A_I} + m_B * V_{B_I} = m_A * V_{A_f} + m_B * V_{B_f}$$

$$m = mass$$

$$V_I = initial\ velocity$$

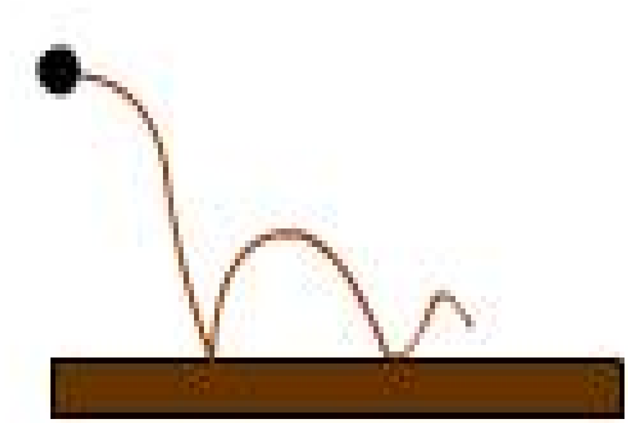
$$V_f = final\ velocity$$

Kinetic energy is conserved.

$$\frac{1}{2} m_A V^2{}_{A_I} + \frac{1}{2} m_B V^2{}_{B_I} = \frac{1}{2} m_A V^2{}_{A_f} + \frac{1}{2} m_B V^2{}_{B_f}$$

Inelastic Collision

An inelastic collision is a collision in which kinetic energy is not conserved, but momentum is still conserved. Some of the kinetic energy from the objects before they collide is converted into heat energy after the objects collide. This heat energy can deform the bodies slightly. The collisions we see in our everyday lives are inelastic collisions. An example of an inelastic collision is dropping a ball from a certain height. When it bounces back up it will not bounce as high. This is because the ball has lost some kinetic energy which has been converted to heat energy.



CENTRIPETAL FORCE

Imagine we placed a ball to the end of a string and spun it around in a circle. This creates centripetal force on the ball. The centripetal force increases if the object moves faster, the mass of the object is increased, or the radius of the circle is decreased. As demonstrated by the equation below.

$$F_c = m * A_c = \frac{mV^2}{R}$$

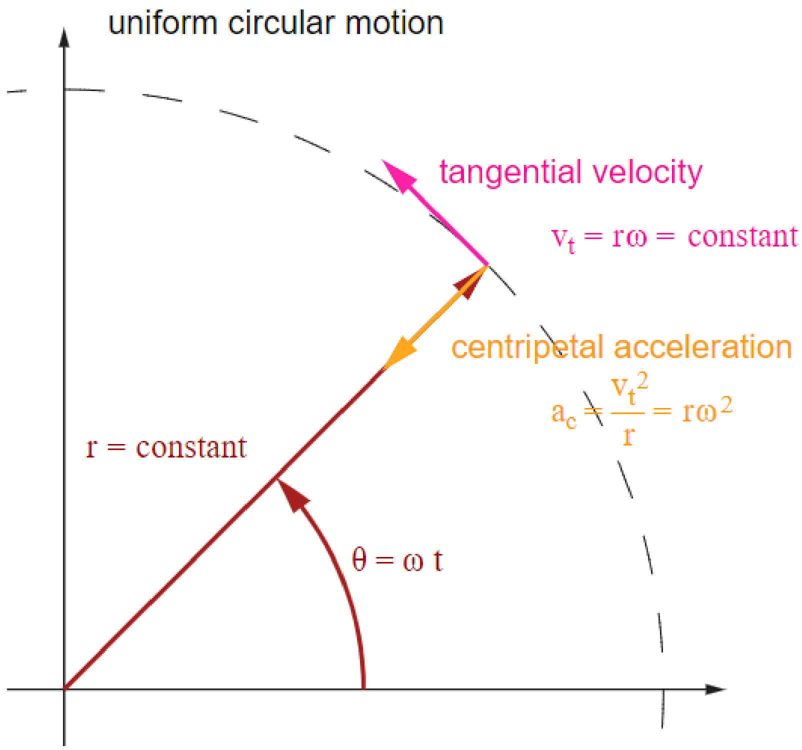
We can also have an expression that allows us to relate the tangential velocity to the radius of the circle and the angular velocity.

$$V_t = r * \omega$$

$$V_t = tangential\ velocity$$

$$r = radius$$

$$\omega = angular\ velocity$$


uniform circular motion
tangential velocity
$v_t = r\omega = $ constant
centripetal acceleration
$a_c = \frac{v_t^2}{r} = r\omega^2$
r = constant
$\theta = \omega t$

RUBE GOLDBERG MACHINE INSTRUCTIONS

POPSICLE STICK LATTICE

A popsicle stick chain reaction is caused due to the stored energy in the over and under weaving of the popsicle sticks. This potential energy is converted into kinetic energy upon release. As the popsicle sticks are weaved together potential energy is gradually being stored in the chain. This is due to the fact that each popsicle stick is slightly bent and naturally wants to return to its original shape. When you release the end of the chain all of the potential energy is released from the chain.

Arrange 6 popsicle sticks in this way and then repeat to make a popsicle stick chain as long as you would like! The popsicle sticks will stay in place until you release them and then they will pop up in a wave like fashion!