

Mousetrap Car 2.0

Engineering Design Challenge

Background Research: Table of Contents

Background

I. The Age of Mechanization (page 2)

Quiz: 4 Reading Comprehension Questions

II. Simple Machines (page 3)

- i. Mechanical Advantage (page 3)
- ii. Lever (page 3)
- iii. Wheel and Axle (page 5)
- iv. Pulley (page 6)
- v. Inclined Plane (page 8)
- vi. Wedge (page 9)
- vii. Screw (page 11)

Quiz: 5 Reading Comprehension Questions

III. Mechanisms (page 13)

Quiz: 8 Reading Comprehension Questions

IV. Mousetrap Car (page 16)

Quiz: 4 Reading Comprehension Questions

Knowledge At Work

V. The Engineering Design Challenge (page 18)

VI. Lever Arm (page 20)

Worksheet: 3 Math Questions (Remember that the radius of a circle = half its diameter!)

VII. Linkage Mechanism (page 21)

Worksheet: 3 Math Questions (Remember that the radius of a circle = half its diameter!)

VIII. Wheel and Axle (page 23)

Worksheet: 4 Math Questions – 2 Calculation, 2 Conceptual

IX. Mass (page 24)

X. Friction (page 27)

XI. Traction (page 32)

XII. Predictive Analysis (page 32)

Quiz: 3 Questions – 1 Reading Comprehension, 2 Math Conceptual

XIII. Optimize (page 34)

PARENTS: Students were asked to read carefully through these Background Research materials before jumping head-first into the Engineering Design of their Mousetrap car so that they had a solid idea of the variables and metrics they should be examining.

They were asked to record notes of Main Ideas and “take-away’s” that could be applied to their own mousetrap cars. It was suggested that 3 bullet-point notes from each section would be sufficient. If students had difficulty in identifying main ideas and concepts, paragraph summaries were suggested as a strategy.

STUDENTS: *Please do not get hung-up on the math!* Some of the physics formulas are intended more for a high school audience, but we (and the Quiz Questions) are primarily concerned with concepts and relationships between variables.

Whitebox has a way of sometimes overcomplicating simple ideas. I’ve tried to highlight (in yellow) key concepts and take-away’s, where appropriate. Rest assured that the extent of the math you’ll be expected to do at this point are one-step algebraic formulas where you are asked to substitute-in values for each variable. If you need assistance, don’t be afraid to ask! ☺
-- Mr. F

*** All Quiz and Worksheet Questions must be accessed Online.**

**** 34 Questions in Total**

I. The Age of Mechanization

The Industrial Revolution

During the Industrial Revolution (1750-1850), society changed from farm-based to a machine-based industry. The textile industry began moving towards a "mechanized" method of manufacturing. This change was combined with an increased ability to produce iron and coal. Railways expanded rapidly, roads were further developed, and steam was used as the power for many machine tools. Trade opened up as people took their focus from an agriculture-based economy to machine-based. More factories were built and more products were made at a faster rate. A higher number of jobs were available in factories. People moved from the country side, which increased city populations. The Industrial Revolution was a time of major transformations in the way people lived their day-to-day lives.

Steam powered the industrial revolution. The Watt Steam Engine was the most famous. With the steam engine, factories could be located anywhere and run off of steam power. Machine tools such as lathes, saws, shovels, and mills ran off steam. In addition, steam was also used for trains, boats, and vehicles. Even though steam was far from a new discovery, it was heavily utilized to power industry. People went from using animals, manual labor, and natural energy sources (wind, water, wood) to using steam engines to do many of their tasks such as grinding, lifting, and moving.

A major invention during the industrial revolution was interchangeable parts. Before interchangeable parts, components of tools were specific and custom to that tool. Parts could only be replaced by a skilled crafts person. One of the earliest mass production products using interchangeable parts was the "sailing block" in 1803. Within five years the Portsmouth Dockyard was producing blocks at an annual rate of 130,000.

Firearms also benefited greatly from interchangeable parts. Before interchangeable parts, when one component of a firearm malfunctioned, it would have to be sent off to an expert for repair. The government took notice of the benefit of interchangeable parts. Eli Whitney, in front of Congress, took the parts of ten firearms all with the same part measurements. He mixed them into a pile only to then reassemble them. Interchangeable parts helped the economy by making it more cost effective to fix complex machines. Mass production using interchangeable parts that could be assembled into tools or machines lead to the revolutionary development of assembly lines.

Machines as a Driving Force

While steam and interchangeable parts were major components of the industrial revolution, tools were also vital. Machine tools became bigger, stronger, and more efficient. Fuel for the machines went from wood to coal, beginning an increased fossil fuel use. People took advantage of coal to produce steam for engines and applied this technology in such areas as mining as well as others. Steam engines allowed miners to more quickly remove water from shafts which enabled them to mine deeper into the Earth's surface. Coal was also used for iron smelting, allowing for increased production of iron for railways, steel for machines and many other uses.

Railways were expanded and more canals were built. Up to this point, canals were not as widely used in areas like Britain, Ireland, and the United States. However, in 1761, the Bridgewater Canal opened, becoming England's first canal. Canal systems allowed for more supplies to be moved around. Coal was heavily transported using canals, and this was achieved at a reduced price than before, due to simpler transportation.

Also vital to the industrial revolution, was the advancement of machine tools. Able to shape and manipulate a variety of materials, the machine tools increased manufacturing capabilities. Components for tools and equipment could be produced efficiently. Products were more available and less expensive. The military took notice and used these methods to increase production of equipment, and to train soldiers in using heavy machinery.

Given the power of the steam engine, it was simple machines that made these new tools work.

II. Simple Machines

Define: Mechanical Advantage

When we use a tool or machine to complete work, we are utilizing the mechanical advantage of a simple machine.

Mechanical Advantage (MA) is the measure of increased output force compared to input force.

In other words, a measurement of how efficiently machines help complete work.

Tools make our lives easier and make it possible to achieve more with the amount of effort we are capable of applying.

Through the use of the Earth's resources, such as coal, oil, water, bio materials and numerous other materials, machines have been designed to produce devices that expand technological development in society. Humans' expanded capability from mechanical advantage has produced advanced developments in the fields of Science, Technology, Engineering, and Mathematics (S.T.E.M.), in addition to others fields.

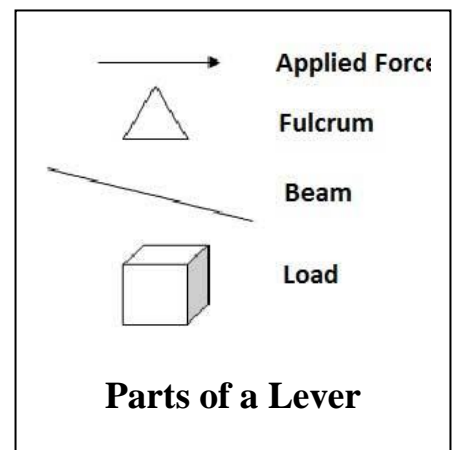
Mechanical advantage is so vital to the development of society that scientists and engineers have developed formulas that calculate the mechanical advantage of simple machines. These formulas take into account the ratio of input force to output force. Basic machines come in six forms and have been highly developed through the development of civilizations.

Six Simple Machines with Typical Applications

Lever

As one of the earliest simple machines, the lever accomplishes many tasks that have strongly benefited society. A lever is a simple machine that operates through the use of a beam, a pivot point upon a fulcrum, as well as an applied force. With the collection of all three components, it is possible to move heavier loads and apply stronger forces. With the ability to increase applied forces and move heavier loads, humans have been able to accomplish things such as building extremely large buildings, designing precise and complex machinery, and engineering solutions to disasters.

The lever has changed the way society functions by allowing vital tools and complex machines to accomplish a variety of tasks. Whether it is the arm of a mouse trap, wire cutters snipping a wire, or the arm of a backhoe, the lever is a vital component of numerous everyday tools and machines.



Mouse Trap

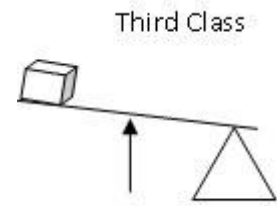
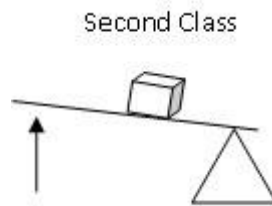
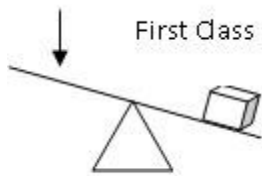


Pliers



Backhoe

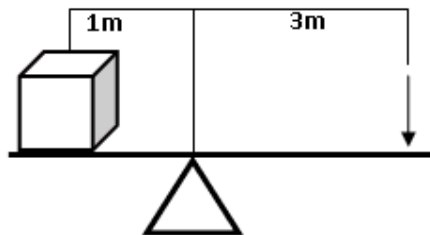
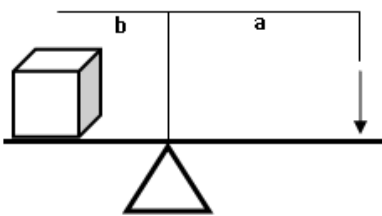
Lever classes come in three classes. The three classes of levers and their uses are as follows:



Even though levers come in three classes, there is one main formula that calculates their mechanical advantage:

$$MA = \frac{a}{b}$$

The ratio of the (a) distance from the fulcrum where input force is applied, and (b) the distance from the fulcrum where the output force is exerted, equals the mechanical advantage of the lever. If distance "a" is greater than distance "b" then mechanical advantage shows an increase in input force, whereas if distance "a" is less than distance "b" mechanical advantage shows a reduction in input force.



You use the lever to the left to raise a box of goods. What is the mechanical advantage of the simple machine you are utilizing?

$$MA = \frac{a}{b} = \frac{3m}{1m}$$

Wheel and Axle

Other tools development that had a huge impact on society are the wheel and axle. Imagine how tools and machines would work if not for these circular and cylindrical objects. The wheel and axle are defined as a wheel attached to an axle which rotates when force is exerted and energy is transmitted throughout. These forces include, but are not limited to, manual labor, water, wind, or energy from another machine. Additionally, these simple machines can be found in an extremely high number of applications of daily life. A wheel and axle should not only be thought of as tires on a vehicle, but as door knobs, gears, rollers, winches, or any other application that involves rotation around an axis.



Steamrollers



Clock Gears



Doorknob

The wheel and axle enabled humans to easily transport objects in larger quantities and over longer distances. Earlier wheels were used on wagons which had 4 wheels and 2 axles. With the capability to expand human travel and increase productivity, the wheel and axle spread in various cultures and was rapidly developed for different applications. At a certain point, the wheel became utilized in the process of making pottery, which was vital to storing food and goods for communities.

Throughout the centuries the wheel and axle went through heavy development. Wind and water mills used wheels and axles to capture energy from the wind and water, and then transfer the force in order to mill wheat. Such applications of the wheel and axle are being applied in methods of alternative energies through wind and water turbines. Wheels and axles have also been used in modern times to develop the assembly line though the use of rollers to transport products through their processing.



Wagon Wheel

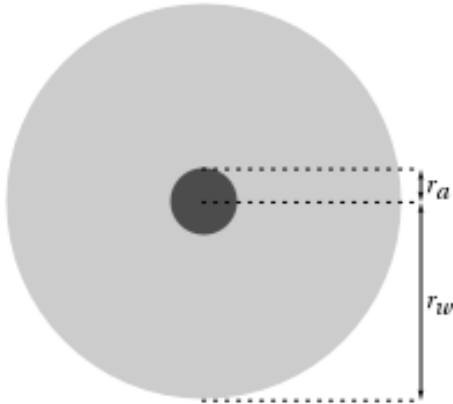


Water Wheel



Wind Turbines

Like all of the simple machines there is a mechanical advantage to using the wheel and axle. The formula for mechanical advantage of a wheel and axle is very similar to the formula for mechanical advantage of a lever.



Mechanical Advantage of a wheel and axle is the result of the ratio between distance "a" (the radius of the wheel) and distance "b" (the radius of the axle). As the ratio increases the force or **torque** is amplified. As you change the size of the wheel or axle then you change the mechanical advantage, as well as the amount of output force. This is highly relevant when it comes to gears in a machine. Output forces can be highly differentiated by changing gear ratios such as in a vehicle, farm equipment, robots, and numerous others.

Pulley

With further development of the wheel and axle came **the pulley, which is a wheel and axle capable of lifting a load, applying a force, as well as changing direction of a force.** A pulley can be used with ropes, belts, or cables to transfer a load. The utilization of pulleys has allowed society to construct buildings and enable tools to function, in addition to transporting people and goods. During the industrial age, as factories became more rooted into communities, the diverse pieces of machinery running production were powered by systems of pulleys.



Pulley System



Water Wheel Pulley



Lift Pulley

Ships throughout the ages have taken advantage of pulleys, to raise heavy sails as well as maneuver anchors. These ships are what enabled nations to expand as well as build trade routes worldwide. Cranes use pulleys to lift heavy loads such as steel beams for skyscrapers or for towing vehicles. We are able to build buildings taller and fill them with people due to elevators which function through the use of pulleys. Manufacturing plants take advantage of pulleys, in the form of conveyor belts, to move goods through an assembly line in order to increase efficiency.



Sailboat



Crane

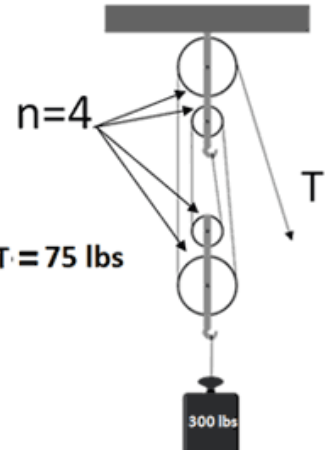
The pulley provides a distinct mechanical advantage for human kind through a variety of methods. **The formula for mechanical advantage is the weight of the load (W) divided by the force of the input effort in lifting or moving the load (T). Mechanical advantage is also equal to "n" which represents the number of times the rope passes through a pulley or how many pulleys are used in the setup.**

$$MA = \frac{W}{T} = n$$

If the load in a pulley system weighed 300lbs (W), what is the mechanical advantage and how much force is required to lift the load (T)?

Note: n=4 because the rope passes through 4 pulleys

$$MA = \frac{W}{T} = n \Rightarrow MA = \frac{300 \text{ lbs}}{T} = 4 \Rightarrow 300 \text{ lbs} = 4 \times T \Rightarrow \frac{300 \text{ lbs}}{4} = T = 75 \text{ lbs}$$



Inclined Plane

Think of all the times you have walked up a ramp walkway or slid down a slide. Both of these are examples of an inclined plane. This simple machine is a flat surface tilted at an angle and is meant to lower or raise loads. Inclined planes are utilized daily for both major and minor purposes. Motocross bikes use inclined planes to launch over long distances whereas a company may use ramps to more easily load goods onto their trucks for delivery. Inclined planes have dramatically affected society in monumental ways such as being required in most buildings in order to provide handicap access. The American with Disabilities Act was passed in 1990 and it covers providing equal rights to those with disabilities. In accordance with the law, government owned buildings and numerous commercial buildings are required to have ramps that provide access to those with disabilities such as an individual in a wheelchair. These inclined planes are required by the government and are in place to provide equal rights to citizens.



Slide



Handicap Ramp



Walkway

Used since ancient times, the inclined plane has been integrated into society to make life easier. In Rome, inclined planes were used in the making of roads. In Egypt, inclined planes were used to move heavy stones. Part of an emergency escape plan of an airplane is to slide down the inflatable ramp to safely make it to the ground - here we have an example of how inclined planes can save lives. Cars and trains can even use inclined planes to make it uphill on roads and tracks. As people have used inclined planes throughout history, they have been able to easily and more safely move objects.



Pyramid of the Moon



Water Landing Craft

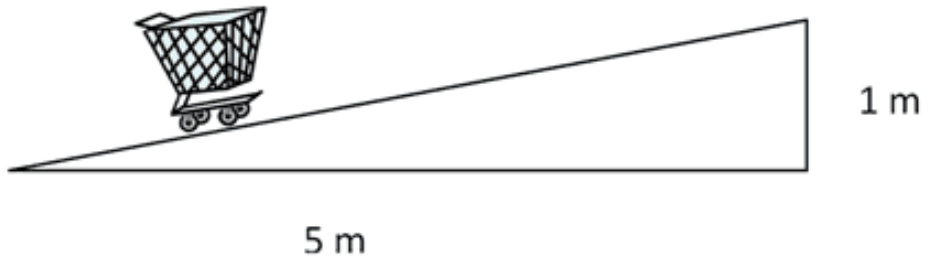
Less force is required to move an object up an inclined plane than to lift it straight up which is key to why inclined planes are so efficient. Mechanical advantage is calculated in two ways: 1) the weight of the load divided by the force required to move it along the inclined plane; 2) the length of the inclined plane divided by its height.

$$MA = \frac{W}{F} = \frac{L}{H}$$

An individual is pushing their cart of groceries weighing 300N up a ramp 5 meters long and 1 meter high.

- What is the mechanical advantage of the inclined plane?
- What force is required to push the cart up the ramp?

$$MA = \frac{L}{H} = \frac{5}{1} = 5$$



$$MA = \frac{W}{F} \Rightarrow 5 = \frac{300 \text{ N}}{F} \Rightarrow 5 \times F = 300 \text{ N} \Rightarrow F = \frac{300 \text{ N}}{5} = 60 \text{ N}$$

Wedge

Inclined planes were further developed and altered to form a wedge which too is a simple machine. **A wedge is a smaller and portable form of two inclined planes combined that have been rounded or sharpened on the edge.** Tools that utilize the wedge are axes, wood splitting wedges, blades, chocks, and a large number of tools meant to split, push, or cut materials. The wedge has drastically affected society by allowing humans to reach a variety of achievements.



Ax



Stone Ax

Ancient man used stones to develop one of the earliest invention - the blade. Stones, such as a flint stone or river bed stones, could be found and shaped as well as sharpened to create a blade. Some of these ancient stones were as sharp as a razor blade. This enabled man to hunt for food, defend themselves, build shelters, develop and shape other tools, as well as develop into intelligent beings. Blades and knives were used to cut plants and to slice meat. Axes were developed and allowed for the cutting down of trees to use for building structures to live in or as a fuel source for staying warm and cooking food.

Time went on and further development of wedges enabled man to accomplish more. Wedges were used in plows to plow fields used to grow crops. Without properly plowed fields, farmers would not be able to harvest food and materials that are required for a society to function. Even tools such as chisels, which were used to construct the most elaborate and meaningful structures, sculptures, and carvings in the world, functioned off of the wedge.



Carving Wood



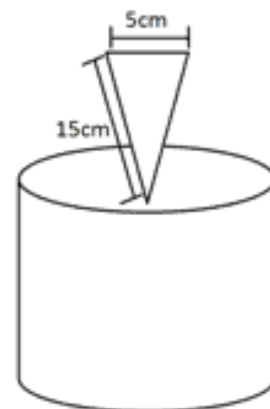
Plow

Calculating the mechanical advantage for a wedge is done by taking its length and dividing that by its width. As the angle of a wedge narrows, or becomes smaller, the mechanical advantage is increased. However, it is important to consider what purpose the wedge is serving before trying to achieve the highest mechanical advantage. Forces, such as friction, may bind or stop a wedge from working due to high mechanical advantages, and may require wider angles instead of the more narrow angles.

$$MA = \frac{L}{W}$$

What is the mechanical advantage of the wedge with a width of 5cm and a length of 15cm?

$$MA = \frac{L}{W} = \frac{15\text{cm}}{5\text{cm}} = 3$$



Screw

Just as the wedge utilizes the inclined plane, so does the screw. **A screw takes an inclined plane and wraps it around a cylinder. The purpose of a screw is to take rotational force, or torque, and transfer it to linear motion.** As one turns a screw around in a wall, the screw moves linearly into the wall. While being one of the later simple machines, first developed in Greece, it is just as important to society as the other simple machines.



Screw



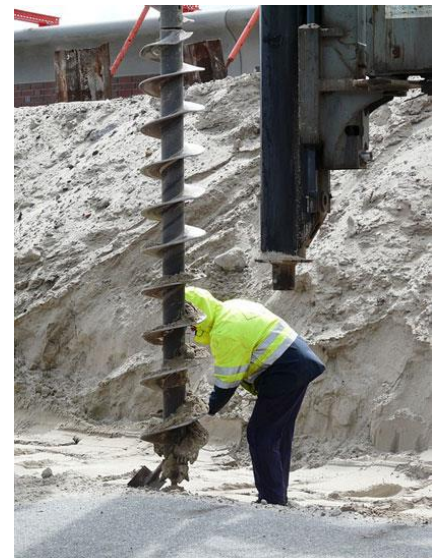
Archimedes Screw

Screws were first used in presses to apply large amounts of pressure to press grapes for wine or press olives for oil. Archimedes took the screw and developed a screw pump that allowed for extracting water from low lying bodies of water. This enabled farmers to irrigate their fields by pumping water from small areas into their fields. With better irrigation came improved harvesting, which led to larger amounts of food and resources to provide to the growing populations. Screws went on to be used to connect materials through the use of nuts and bolts, wood, and metal screws. Many clamps that are used to hold material together when working on them use the screw design to function.

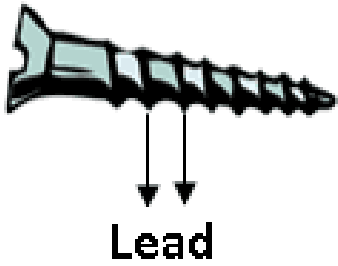
Even today the screw has taken a huge role in society. While constructing networks of pipes, augers are used to remove materials from surfaces such as land. An auger will remove earth to allow for pipes to be installed. These pipes can carry water, fuel, or waste material. Many of the products we use today take advantage of the screw to provide self locking functions. Jars require screws to open and close. Bottles use caps that screw on and off.



Bottle Cap



Auger Drill



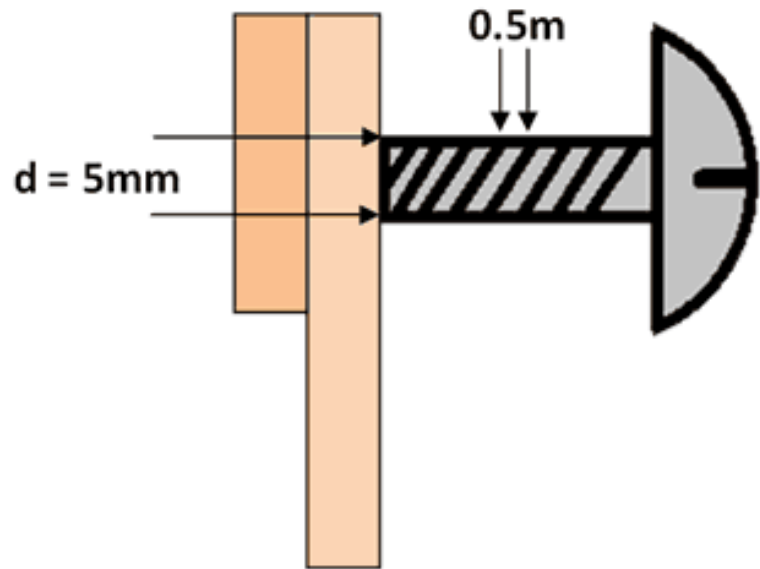
While calculating the mechanical advantage of a screw the "lead" must be measured and used. The linear distance the screw travels in one rotation is the lead of a screw. Smaller leads increase mechanical advantage.

Dividing $2\pi r$ (r =radius of screw) by the lead results in the mechanical advantage. You can also calculate mechanical advantage by dividing the amount of output force of the screw by the input force.

$$MA = \frac{F_{out}}{F_{in}} = \frac{2\pi r}{l}$$

Calculate the mechanical advantage of the screw used to connect two pieces of materials using the information to the right.

Note: $r = 1/2d$



$$MA = \frac{F_{out}}{F_{in}} = \frac{2\pi r}{l} = \frac{2\pi 2.5\text{mm}}{.5\text{m}} = 31.4$$

III. Mechanisms

Mechanisms

Mechanisms are a collection of simple machines that form a system that does work. With all the components, working as a system, these mechanisms can achieve a variety of goals using both moving and fixed parts.



Mechanism

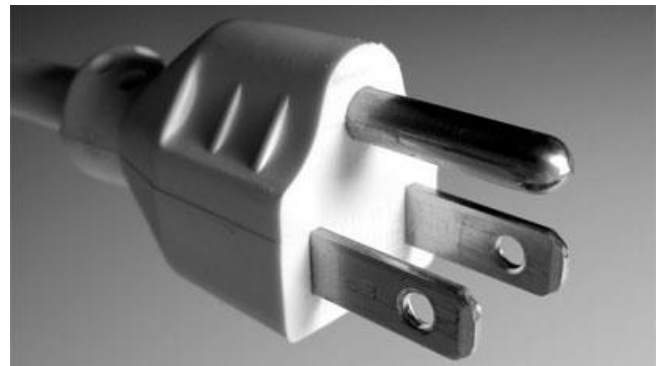
Power Source

Machines require a power source to provide an input force. The power source can be from nature or produced by humans. For thousands of years water and wind have been used as a power source for machines such as mills or water pumps. Natural energy sources are still being used today such as wind turbines and hydroelectric dams to produce electricity.

The electricity produced from power plants is the power source for many of the tools we use every day. From power tools to game systems, electricity acts as a power source for much of our technologies. Many of the toys and tools not powered by electricity use simple machines in addition to humans as power sources. **If you take a spring, wind it up, and release the energy you can power anything from a watch to a mousetrap.**



Wind Turbines



Plug

Powertrain

Just because a machine has a power source does not mean it will function properly - it must have a powertrain.

A powertrain is the system of simple machines that takes the input energy and puts it to use. This includes a team of components such as levers, gears, shafts, axles and wheels.

The powertrain is designed to convert energy from the power source to perform a function. In many cases, a transmission is used to transfer such energy by using gears. These rotating toothed machines are used in numerous daily applications. One use for gears to transfer energy is the automobile. Vehicles, regardless of power type, use gears to transfer energy from a motor to produce movement. Differentials are made up of a number of gears which transfer rotational energy from the motor to other components of machines. A drive

shaft carries torque over a certain length to different areas of a machine. As all these pieces function together in a system, our machines and tools can operate properly to make life easier and help society further develop.



DC Motor



Differential



Driveshaft

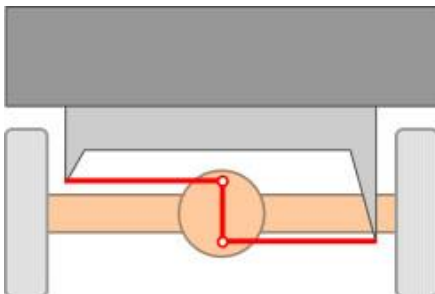
Linkages

In order for the powertrain to function properly, it requires linkages for each component. These linkages are a system of links connected at joints with rotary or linear bearings that allow movement to transfer through simple machines such as a lever and fulcrum. Linkages can be in place for a variety of reasons and contain both fixed as well as pivoting points.

These fixed and pivoting points enable linkages to transfer motion from rotational to linear and vice versa. Linkages have been used for thousands of years in machines by taking advantage of simple machines. They come in all sorts of designs, each with a specific purpose. Linkages are not just randomly designed but are developed using mathematical concepts and can range from basic to extremely complex applications. Some of the more historical linkages that have affected society are as follows:

Watt's linkage

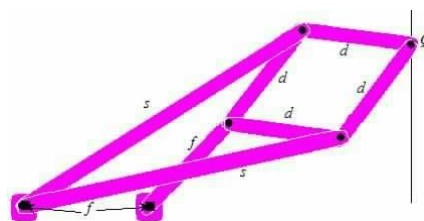
This consists of a four-bar linkage design that generates an approximate straight line. Once it was developed, it was vital to the operation of Watt's design for his steam engine.



Watt's Linkage

The Peaucellier linkage

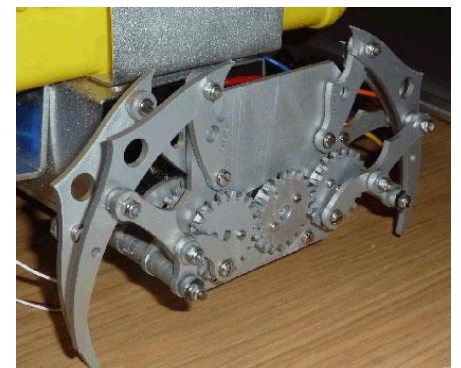
Generates a true straight-line output from a rotary input.



Peaucellier Linkage

The Klann / Jansen Linkage

Recent designs enable walking movements through the use of six-bar and eight-bar linkages. Such developments provide machines the ability to move over complex terrain and complete complicated tasks.



Klann Linkage

Structural Components

The structure secures the parts in place so everything works together. All parts of a machine must be housed, secured, and connected to allow proper function. The structure must be strong enough to prevent the breaking or moving of parts.

Frames - Using beams, trusses, and similar structural elements, a frame is designed to keep vital parts together. The frame is designed so the components work as a system.



A motorcycle frame contains all of the components of the machine

Bearings - When a machine has moving parts that cause friction between components, then a bearing is desired. A bearing allows for rotational and linear movement while reducing friction.



Ball Bearing

Mounts - Mounts secure the mechanical components of a machine to the frame as well as other parts.

Splines / Keys - These allow for two objects that rotate to mount to each other. Splines and keys are used to attach gears to shafts or wheels to axles. Torque can be transferred efficiently by having a secure mount.



Notice the spline in the middle of this driveshaft connecting the two components and transferring torque.

Springs - Components of a machine can be suspended or held in place by using a spring. A spring also allows for movement on a lever and can absorb vibration which protects other parts. In some cases, a spring can be used as a power source for machines.



Mousetrap powered a by spring in the middle.

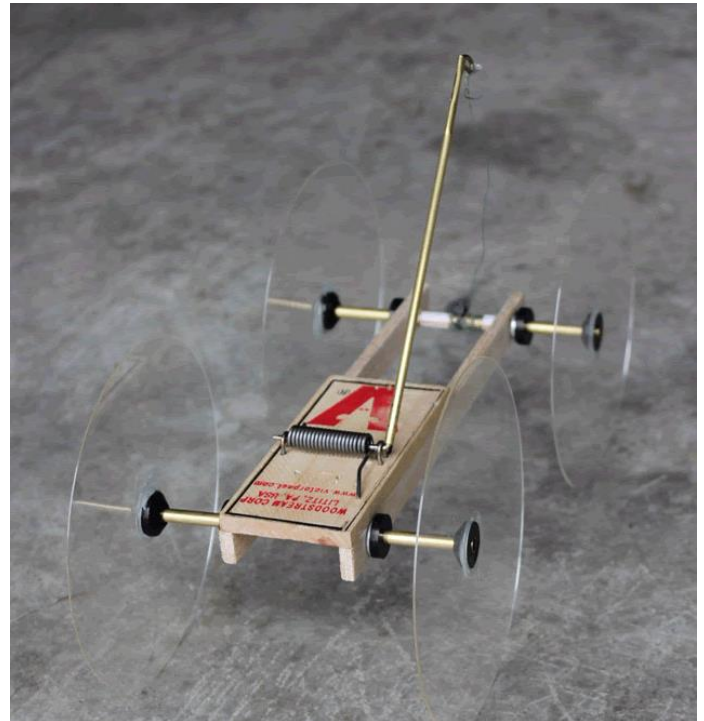
Fasteners - As a machine is assembled, the components are attached using fasteners. These can include rivets, screws, nuts and bolts. While these fasteners are removable, some fastening techniques such as welding and adhesives are permanent.



Rivets on end of a metal pipe

IV. Mousetrap Car

All of the simple machines, linkages, structural components, and other pieces come together to make up machines and tools that have helped society develop into what it is today. These technologies are woven into all aspects of lives. Take the vehicle as an example of a technology that has changed the way we live. Over thousands of years various resources such as steam power, wheels and axles, levers, gears, metalsmithing, and others came together to form the first vehicle. From then on, the vehicle was engineered to run on different fuel sources and maneuver over various types of terrain. Vehicles allowed man to move more and heavier goods across further distances which increased jobs, trade, and the ability to travel. A good model of the basic components of a vehicle as well as numerous other technologies is a mousetrap car.



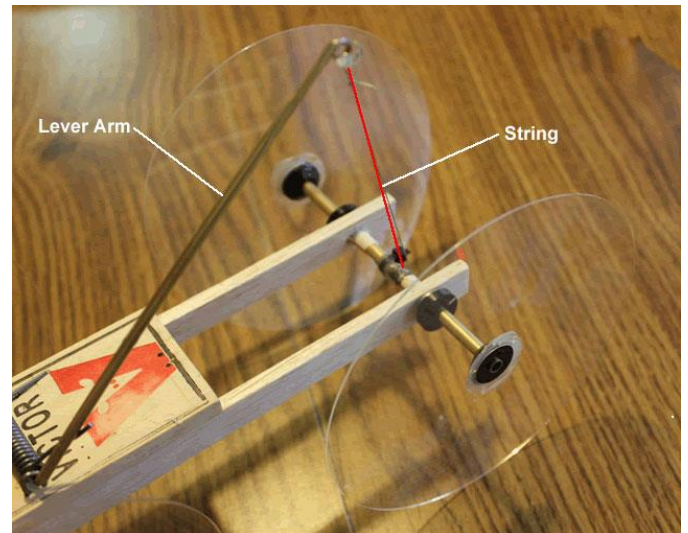
Power Source (spring)

The power source of the mousetrap is a spring. When springs are wound and held they contain potential energy. Once released, springs convert that potential energy into kinetic energy. This can also be seen in toy cars. Some toy cars are powered by having the user put the toy car on a surface, pull the car back a few inches (this winds the spring), and then release it allowing for it to speed forward. **When building your mousetrap car, remember that springs can have different tensions. Tension can be thought of as the force that occurs as something is tightened or loosened. As a spring is wound up, its tension becomes higher and tighter.**



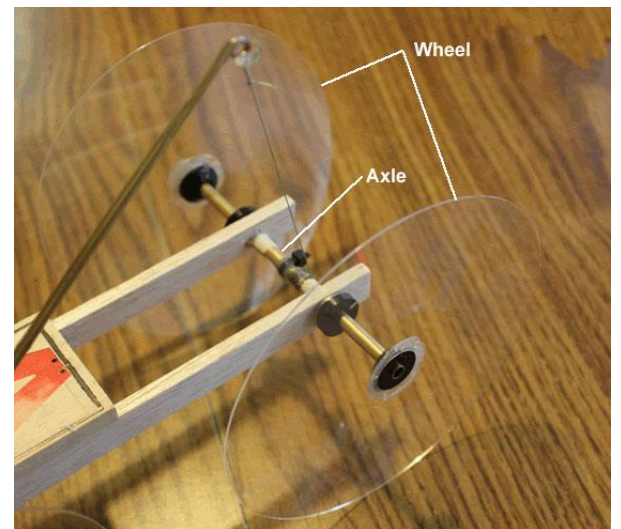
Powertrain (lever and linkage)

Acting as a powertrain that transfers energy from the spring motor to tires are the lever, string, as well as the wheel and axle. On a mousetrap, a spring is connected to a lever. As the spring is released it transfers its torque to the lever. This causes the lever to follow the spring and apply its force over a greater distance. The mechanism also acts as a linkage, transferring energy from the pivot point of the spring along the lever arm and to a string attached to the lever. The string is attached to the lever at one end, and is wound around the axle at the other end. This transfers the energy from the lever to the wheels and axles.



Wheels and Axles

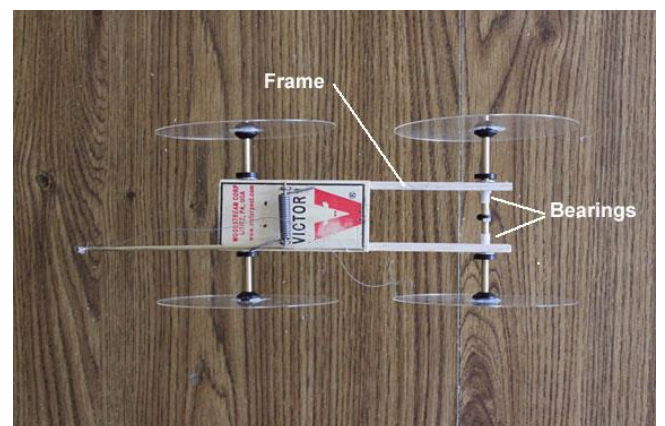
As the string is pulled by the lever it unwinds from the axle, transferring energy from the lever arm to the wheels. The unraveling rotates the axle which, with the wheels attached, transfers the energy through the axle to the wheels and to the surface. This enables the vehicle to roll forward. The distance traveled using the wheels and axles depends on numerous things such as spring tension, length of string to unravel, friction having to be overcome, texture of surface the vehicle is driving on, in addition to the weight of the vehicle as well as the type and material of the wheels being used.



Structure

While all of these components function together to power and transfer energy throughout the vehicle, none of this would be possible without a structure to mount, house, and secure the pieces. The structure of the mousetrap is the wooden platform of the mousetrap as well as the built frame that houses the powertrain. This wooden frame has the spring mounted with the lever arm and string attached to the wheels and axles. The wheels and axles can even be mounted to the mousetrap car using bearings which can reduce friction. The frame can also hold cargo being transported by the vehicle. No

matter how well you have engineered your components, they will not function properly without a proper frame to secure them together that allows for all pieces to work as they are designed.



The Engineering Design Challenge

When defining an engineering design problem, the purpose or function of the device helps define the design constraints. Mousetrap cars use simple machines in combination to produce the force needed to propel the vehicle forward. **The vehicle can be designed for speed or distance, or a combination of both** based upon the specs your teacher dials in for your challenge. **Vehicles designed for speed must get off the line quick and accelerate fast to the finish line. Designing for distance requires less torque at the starting line with the intent to maximize the number for revolutions under power.**

Either way, there needs to be enough force to overcome resistance to get off the starting line and move forward. How can we engineer a vehicle for a designed purpose? Well, let's "do the math".

Sir Isaac Newton's theories on motion defines 3 Laws of Motion. His second law of motion states:

The acceleration of an object of constant mass is proportional to the force acting upon it.

In mathematical form, the relationship of force, mass and acceleration is defined as:

$$\textit{Force} = \textit{mass} \times \textit{acceleration}$$

$$F = m \times a$$

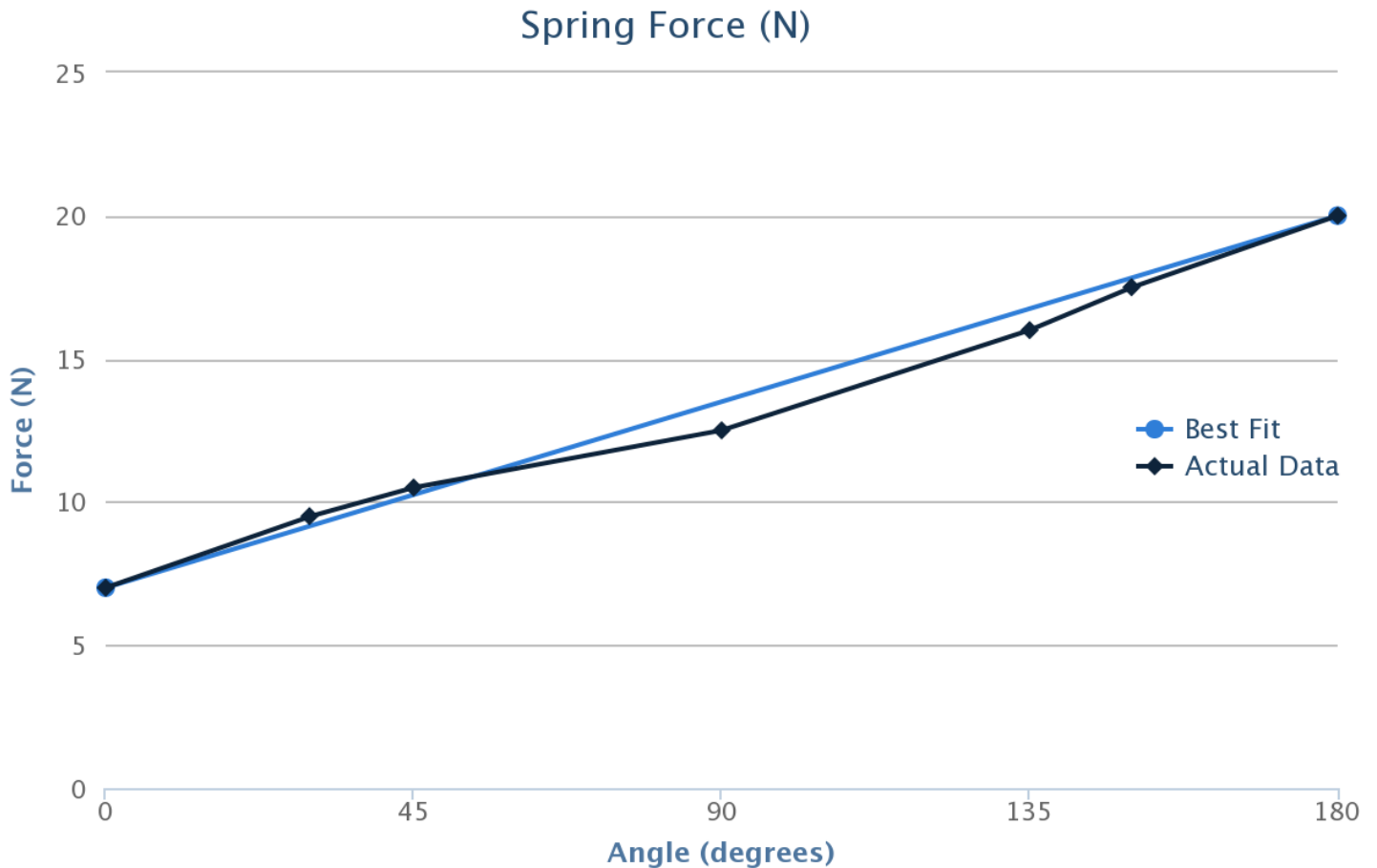
Solving for acceleration we find that:

$$a = F / m$$

Therefore, to calculate acceleration we need to know the force or net force acting on the vehicle and total mass of the vehicle. Let's start with propulsion force.

Spring Force

The engine of this vehicle is spring tension that produces force. When a spring is wound, the force required to wind the spring is converted to spring tension. As you may expect, the force needed to wind the spring increases as the spring is wound. Thus, when the spring is released, the force is greatest when released then decreases as the spring unwinds. The graph below shows the force produced by a standard mousetrap when wound 180 degrees. As you can see from the graph, **there is a linear relationship between force and angle when the arm is released. The slope of this line is called the spring constant.**



The spring constant or slope of a line can be found using the following equation: $Slope = \frac{(Y_2 - Y_1)}{(X_2 - X_1)}$

Essentially, the change in force (y-axis) is divided by the change in degrees (x-axis). Selecting the start and end point from the graph we have:

$$Slope = \frac{(20 - 7)}{(180 - 0)}$$

$$Slope = \frac{13}{180} = .072$$

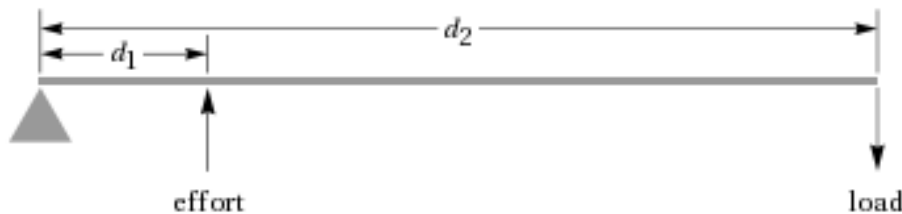
Once the slope is known, the force of the spring at any point in the process of unwinding can be found by using the straight line equation:

$$y = mx + b$$

Where $m = \text{Slope}$, and b is the y-axis intercept. The total force produced by the spring is a calculation of the area under the curve or approximately the average of the force produced. As shown in the graph, the starting force produced by the spring is 20N.

Lever Arm

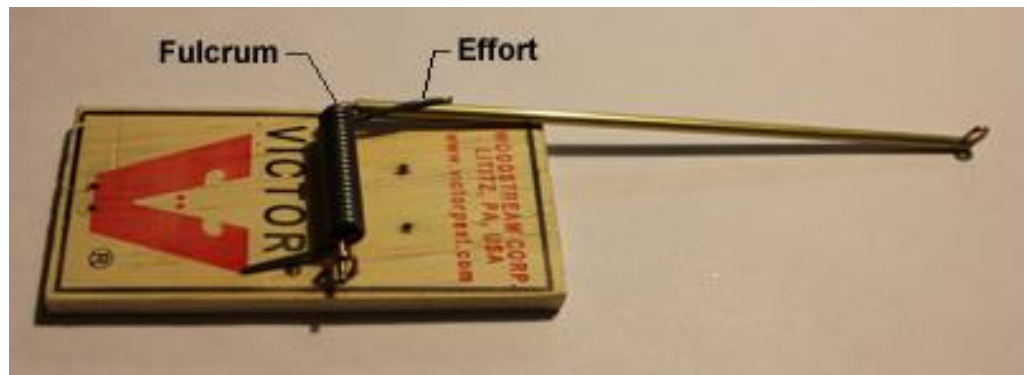
The powertrain mechanism of the vehicle includes the lever arm that is attached to the spring to transfer the spring force to the axle via a drive string. As you learned previously, class 1 and 2 levers increase force output by sacrificing the distance the force is applied. **Class 3 levers increase the distance the force is applied by sacrificing force output.** **To determine the mechanical advantage of a class 3 lever, you must calculate the ratio of the distance from the fulcrum to the effort (d_1) and the fulcrum to the load (d_2).**



Mechanical Advantage of Lever Arm

$$MA = \frac{d_1}{d_2}$$

With a mousetrap powered vehicle, the fulcrum of the lever arm is the spring center and the force or effort is applied 17mm from the fulcrum.



For a 315mm length lever arm, the Mechanical Advantage (MA) is:

$$d_1 = 17mm$$

$$d_2 = 315mm$$

$$MA = \frac{17mm}{315mm} = .054$$

Therefore, the force transferred to the axle at the starting line is:

$$Force_{lever\ arm} = MA \times Force_{spring}$$

$$= .054 \times 20N$$

$$= 1.06N$$

Linkage Mechanism

String is used to transfer the force at the lever arm to the axle. The string provides a pulling force that rotates the axle. Rotational force is called torque. Torque is equal to the radius of the axle multiplied by the force.

$$T = \text{Radius} \times \text{Force}$$

The typical axle has a diameter of 4.76mm. So, the radius is half the diameter or $4.76\text{mm} / 2 = 2.38\text{mm}$. The unit of torque is a Newton meter. To solve for torque, the radius must be converted to meters, $2.38\text{mm} = .00238\text{m}$. Therefore:

$$T = .00238\text{m} \times 1.06\text{N}$$

$$T = 0.0025 \text{ Nm}$$

As you can see from the equation, torque can be increased by increasing the axle radius since it is a multiplier. A spool with a radius of 9.5mm or .0095m attached to the axle would increase the torque to:

$$T = .0095\text{m} \times 1.06\text{N}$$

$$T = .01\text{Nm}$$

As we have found with simple machines, if we increase force, it is at the cost of decreasing distance. In this case, it is the number of revolutions the axle turns. The number of revolutions the axle turns is dependent on the lever arm travel which determines the length of string and the circumference of the axle or spool. The length of the string is equal to the travel of the lever arm plus the distance from the loaded lever arm to the axle.

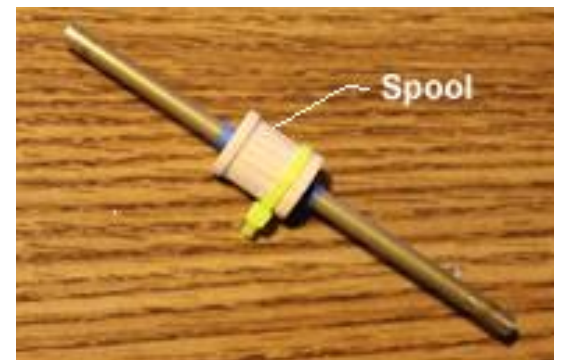
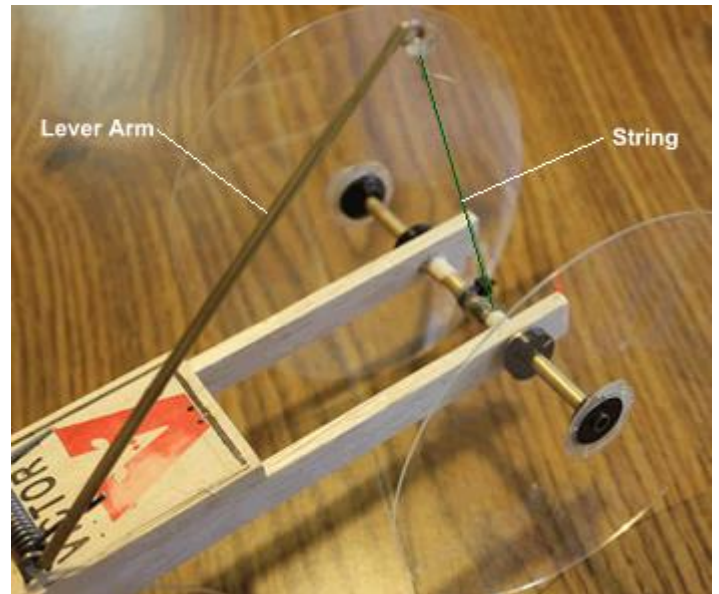
$$\text{String Length} = (\text{Lever Arm Length} \times 2) + \text{Arm to Axle Length}$$

$$S_L = (315\text{mm} \times 2) + 20\text{mm}$$

$$S_L = 650\text{mm}$$

We can calculate the number of revolutions by knowing the length of string needed to wrap one revolution. This length is the circumference of the axle or spool. The circumference of a circle is equal to pi (3.14) times the diameter:

$$C = \pi \times d$$



With an axle diameter of 4.76mm, the circumference is:

$$C = 3.14 \times 4.76\text{mm}$$

$$C = 14.9\text{mm}$$

The number of revolutions is equal to the string length divided by the circumference.

$$\text{Revolutions}(R) = \frac{S_L}{C}$$

$$R_{\text{axle}} = \frac{650\text{mm}}{14.9\text{mm}}$$

$$R_{\text{axle}} = 43.6 \text{ revolutions}$$

Let's compare that result to the number of revolutions using a spool to increase force. A spool with a 19mm diameter has a circumference of 59.66mm (3.14 x 19mm), so the number of revolutions can be calculated as follows:

$$R_{\text{spool}} = \frac{650\text{mm}}{59.66\text{mm}}$$

$$R_{\text{spool}} = 10.9 \text{ revolutions}$$

So, we can see that **a decision to use the mechanical advantage of a simple machine has trade-offs.**

	Axle Only	Axle with Spool
Torque	0.0025Nm	0.01Nm
Revolutions	43.6	10.9

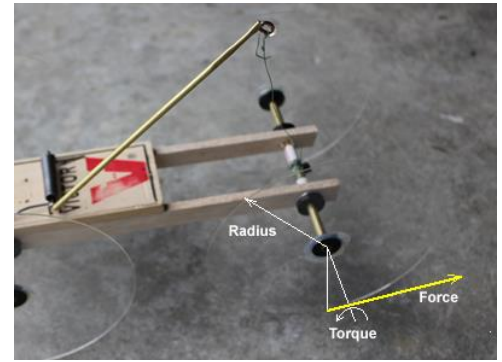
As you can see from the table above, **with the increase in torque there is a decrease in the number of revolutions.** Why is this important? The number of revolutions determines the distance traveled under power as you will learn in the next section.

Wheel and Axle

The wheel and tire are the final components in the simple machine mechanism.

The wheel and tire converts the rotational force of the axle into the force that propels the vehicle. The tire provides the friction needed to ensure the force moves the vehicle forward rather than just spinning the wheels.

Again, the wheel and axle is a simple machine that results in a mechanical advantage that can be used to increase the force on the road or the distance under power.



Force

As mentioned previously, **the rotational force of the axle is called torque**. As we calculated in the previous section, torque at the axle is .00235Nm. The force at the wheel that propels the vehicle is a function of the axle torque and the mechanical advantage of the wheel and axle combination. The force on the road is equal to the torque divided by the wheel radius.

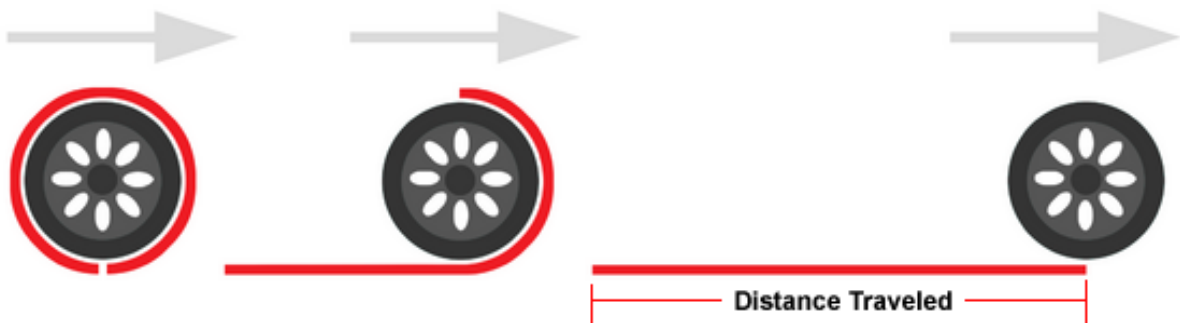
$$F = \frac{T}{r}$$

Given a wheel with a radius of 60mm or .06m, the force propelling the vehicle from the starting line is:

$$F = \frac{.00235Nm}{.06m}$$
$$F = .039N$$

Distance

From the previous section we calculated the number of revolutions that the axle would turn. With the designed drive train linkage, the axle will rotate 43.6 revolutions. A wheel will travel its circumference in one revolution.



Therefore, the distance under power is equal to the circumference of the wheel multiplied by the number of revolutions.

$$distance = (3.14 \times .12m) \times 43.6$$

As we can see from the torque equation, **if the radius of the wheel is increased, the force will decrease. However, the distances under power will increase.**

Below is a comparison chart showing force and distance variables with and without the axle spool for different wheel size.

	0.06m Radius	0.09m Radius
Starting Force	0.039N	0.026N
Distance Under Power	16.4m	24.6m

Mass

Mass is similar to the weight of the vehicle, but there is a difference between the mass of an object and how much it weighs. **Mass is a measure of the amount of matter or material an object contains. Weight takes into account gravitational pull. For example, the moon's gravitational pull is much less than the earth's. Your car would weigh less on the moon but the mass would be the same. Since all testing will occur on earth, the difference between mass and weight factors out. If your car weighs less than your classmate's car, it has less mass.**

So how do we go about changing the mass of a car? To answer this, let's take a closer look at what mass really is.

$$\text{mass } (m) = \text{density } (p) \times \text{volume } (v)$$

This equation shows that the mass of an object depends on a variable called **density**, and the **volume** of an object. **All materials have a unique density, and as the following table shows, they vary a lot.**

The density of steel, for example, is approximately 7.84 grams per cubic centimeter. In other words, a 1 centimeter cube of steel would have a mass of 7.84 grams.

Balsa wood has a density of 0.17 grams per cubic centimeter. So a 1 centimeter cube of balsa wood would have a mass of 0.17 grams.

To put things into perspective, if you designed a vehicle with steel rails, it would have to be about the size of your thumb to have the same mass as the others made of balsa wood.

	Density (g/mm ³)	Tensile Strength (MPa)
Brass	.00855	45,700
Steel	.00784	4,800
Aluminum	.00264	3,800
Plastic	.0010	4,000
Pine (Ponderosa)	.00054	406
Basswood	.00041	384
Balsa	.00017	150

Since **Newton's second law tells us that decreasing mass will increase acceleration, then the lightest possible materials and minimum volumes must be the way to go, right? Well, not necessarily. Generally, lighter materials are not as strong as heavier materials. From our table, we can see that basswood is more than twice as heavy as balsa wood, but it is also more than twice as strong. So, if you want your vehicle to last longer, you may want to consider using basswood; however, you would be sacrificing speed.**

Body frame design is not the only thing to consider when it comes to mass. The total mass of your vehicle includes the mass of the wheels, axles, bearings, and the mousetrap and lever arm. The table that follows shows the mass of each component of Whitebox Learning's basic kit, the "Machine Racer: Rally" kit.

Component	Material	Qty.	Unit Weight (g)	Total Weight (g)
Side Rails	Balsa	2	1.4	2.8
Mousetrap	Steel-Wood	1	18.1	18.1
Lever Arm Assembly	Brass	1	5.1	5.1
Axle	Brass	2	4.6	9.2
CD/DVD Wheel	Plastic	4	7.7	30.8
Wheel Bushing / Spacer	Rubber	8	1.3	10.4
Thrust Washer	Steel	4	1.2	4.8
Total				81.2

The way to reduce total mass is to reduce the mass of one or more components. When considering axle selection, for example, can we say that aluminum is always a better choice than brass because it is lighter? Not necessarily. As we'll see later, a brass axle may produce less surface friction than aluminum. So, it's possible that a heavier axle will result in a faster car. Once again, we have an interesting trade off to consider.

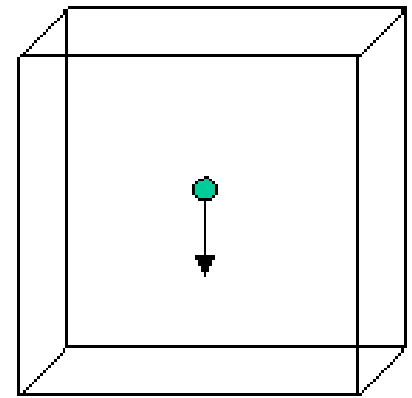
Center of Mass

As you have learned, the total mass of the vehicle is important. How this mass is distributed is also important. **The center of mass is an object's "balance point".** For example, if you could balance a mousetrap car on the tip of a pencil, the pencil would be just below the center of mass. This literally means that half of the car's mass is on either side of the pencil.

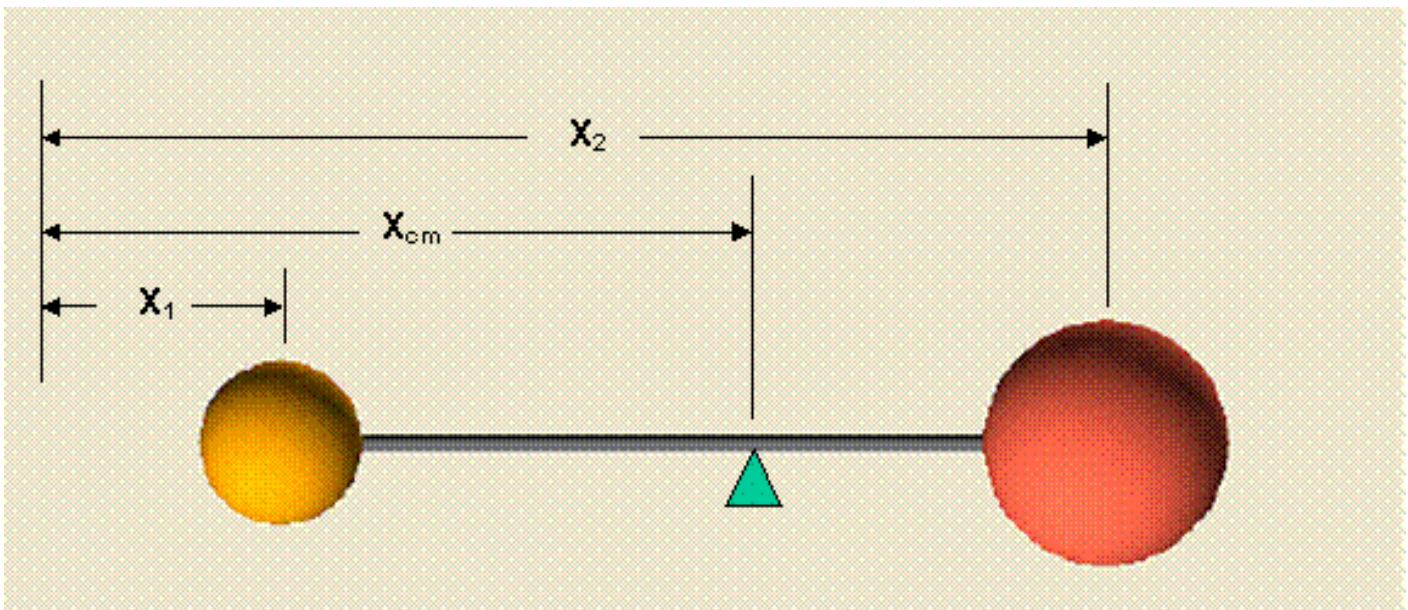
The center of mass is a point. It has an x-coordinate and a y-coordinate, and both are important for different reasons. **Its position from the ground (y-coordinate) affects the stability of the vehicle.** Its position from the rear (x-coordinate) determines the distribution of mass between the front and rear axle assemblies. Both of these factors are important in the design of a mousetrap car. We'll address stability here. The importance of the distribution of mass will be more clear when you learn about surface friction.

Calculating the center of mass can be pretty easy when it comes to simple objects like cubes and spheres. For these and other symmetrical objects made of a single material, the center of mass is the geometric center. But for more complicated objects, such as asymmetrical shapes or composite objects – objects with a combination of different components and materials – the center of mass is much more difficult to determine.

Your mousetrap car will be one of these more complicated objects. More than likely, you will design a body shape that is anything but simple. Your design will also consist of many different components and different materials. When calculating the center of mass for your car, we'll need to consider all these components and calculate a "composite" center of mass.



The application will automatically calculate your vehicle's composite center of mass for you, but it's important that you understand the contributing variables so that you can make informed design decisions. Let's start by considering a "barbell" with different masses on each end of the bar.



$$x_{cm} = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2}$$

This equation defines the x coordinate of the composite center of mass for the barbell. In this case there are only two objects (if we ignore the handle). As objects are added, the x and y coordinates for the composite center of mass will be defined as follows.

$$x_{cm} = \frac{m_1 x_1 + m_2 x_2 + \dots m_n x_n}{m_1 + m_2 + \dots m_n}$$

$$y_{cm} = \frac{m_1 y_1 + m_2 y_2 + \dots m_n y_n}{m_1 + m_2 + \dots m_n}$$

These formulas are much simpler than they look. What they essentially say is that each individual component in the system will affect the overall or composite center of mass by an amount consistent with its contribution to overall mass. **If you increase the mass of the front axle assembly, for example, this will shift the overall center of mass forward and down.**

Friction Force

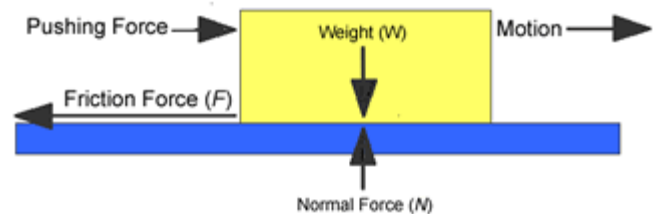
Friction force is the resistive force that must be overcome to move the vehicle forward, and the force that slows the vehicle to a stop when the power has been depleted. If there were no resistive forces, your vehicle would continue to travel at its maximum speed forever. If you take your foot off the accelerator in a car, the car slows down. Likewise, when the power from the mousetrap has ended, the vehicle slows down. The force that slows the vehicle is called friction.

Sliding Friction

Friction occurs when two surfaces are in contact and a force is moving one surface over the other. For example, if you push a wood block across your desk, friction will resist the motion of the block and bring it to a stop. Friction is caused by the roughness of the two objects in contact. Even two materials that seem very smooth have some degree of roughness. Viewing surfaces under a microscope can be very revealing.

We can measure the force of friction between two surfaces if we know the normal force between them (N) and a variable called the coefficient of friction (μ). Here's the formula:

$$F_f = \mu N$$



In the case of our block sliding over the desktop, the normal force is simply the weight of the block, which is the mass of the block multiplied by the acceleration of gravity (weight = mg). The coefficient of friction is a unique variable representing the two surfaces in contact.

Material 1	Material 2	Friction Coefficient
Copper	Steel	0.53
Graphite	Steel	0.10
Polystyrene	Steel	0.35
Steel	Brass	0.51
Wood	Metal	0.60

In our simple example above, let's assume that our block is wood and the desktop is metal. The table below shows that the friction coefficient is 0.60. So if the mass of our block were 50g, then we could calculate the force of friction.

First, let's calculate the normal force (N). N is equal to mass times the acceleration of gravity. To keep the units equivalent, grams must be converted to kilograms. Dividing grams by 1000 converts them to kilograms so $50g = .05kg$. In this case, acceleration is the acceleration of gravity pulling on the block.

The acceleration of gravity is a constant equal to 9.81 meters per second per second (m/s/s).

Therefore:

$$N = 0.05kg \times 9.81 \frac{m}{s^2} = 0.49N$$

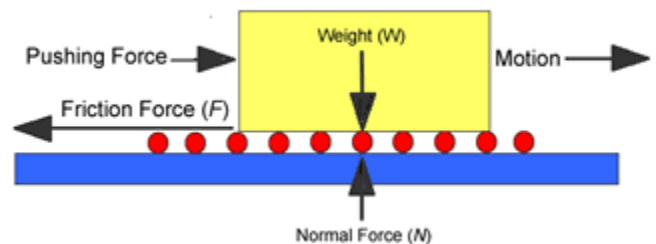
Back to our friction equation, given a coefficient of friction of 0.60, the friction force is:

$$F = 0.60 \times 0.49 = .029 N$$

Let's say that our block is now made of steel and the desktop is covered with plastic (polystyrene). Our friction table shows us that the coefficient of friction is now 0.35 – much lower than our previous example of wood and metal. If we assume that the mass of the steel block is also 50g, what would the force of friction be? Would you expect the steel block to slide further? Remember, if the force of friction is low, then the resistance to forward motion is low.

Rolling Friction

Rolling friction is a force that resists the motion of wheels. Rolling friction will slow your vehicle but it is much less than sliding friction. Think about it. Place a wheel, marble and wood block on a board. Slowly raise one end of the board. What object will move first? **Rolling force is very small in comparison to sliding force.**



Friction Forces on Your Vehicle

On a mousetrap vehicle, surface friction occurs between the wheels and track surface and between each axle and bearing surface. The axle is typically a brass tube. **The bearing is whatever surface the axle is in contact with. This may be the vehicle's side rails if no explicit bearing is selected or, perhaps a plastic straw.** The friction force at each of these locations is a function of a unique coefficient of friction between the contact materials and the normal force at each location. On a vehicle, the four locations producing friction force:

1. Front wheel and track (F_{fw})
2. Rear wheel and track (F_{rw})
3. Front Axle and Bearing (F_{fa})
4. Rear Axle and Bearing (F_{ra})

Thus, the total friction force is:

$$F_{tot} = F_{fw} + F_{rw} + F_{fa} + F_{ra}$$

This equation is long but not complicated. It simply adds the force at each point to get total force. As the friction formula shows, to calculate friction force we need to know the coefficient of friction (μ) and the normal force (N) for each of the four sources of friction.

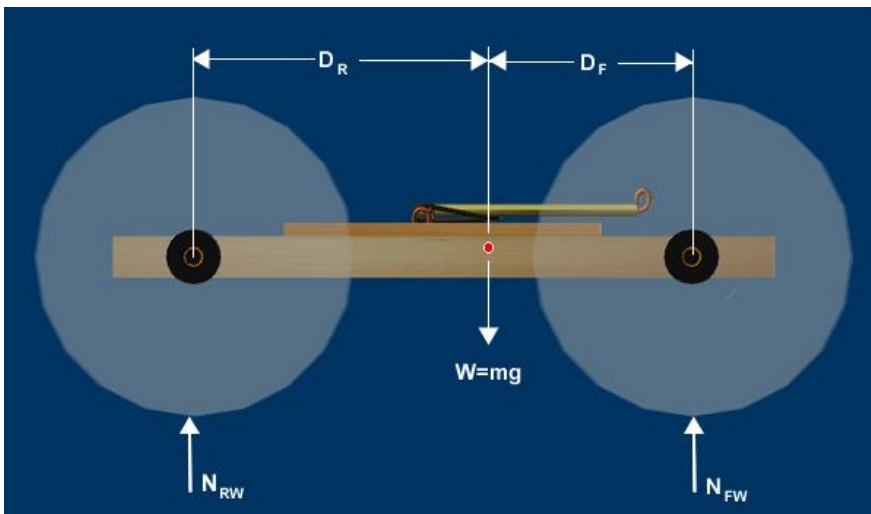
The coefficient of friction for wheels, axles, and bearings depends on the materials used for each of these parts. The coefficient of friction for axle assembly components commonly used on mousetrap vehicles is listed in the following table.

	Coefficient for Axle Type				
Bearing Type	Steel	Brass	Delrin	Aluminum	Chrome
No Bearing (Wood)	0.0618	0.0408	0.0392	0.0534	0.0484
Plastic Straw	0.0554	0.0238	0.0282	0.0325	0.0317
Laminated Bushing	0.0184	0.0140	0.0132	0.0180	0.0174
Brass Bushing	0.0205	0.0187	0.0142	0.0232	0.0182
Ultimate Bushing	0.0157	0.0092	0.0139	0.0185	0.0168

The wheel rolling on the track produces a friction force. The table to the right shows the coefficient of friction for manufactured wheels rolling on a common track surface, plastic.

These coefficients are low compared to axle and bearing coefficients. This should not be surprising, however, since wheels roll over the track surface, while axles turn (or slide) inside the bearing. Does this mean that we can ignore the friction that occurs between the wheel and track? Sorry, but no. We also have to consider the normal force, and the normal force is always greater at the track surface than at the bearing.

Type	Wheel	Coefficient
Front	Plastic CD	0.0035
	Front Racer	0.0085
Rear	Plastic CD	0.0035
	Rear Racer	0.009



First, let's look at the normal forces between the wheels and the track surface. In this case, the total normal force is simply the weight of the car. But we need to know how this total force is distributed between the front and rear wheels. Here's an illustration of a typical car with the relevant variables.

The normal forces at the rear and front wheels are represented by the variables N_{rw} and N_{fw} . The sum of these two forces will equal the total weight of the vehicle.

$$W = mg = N_{rw} + N_{fw}$$

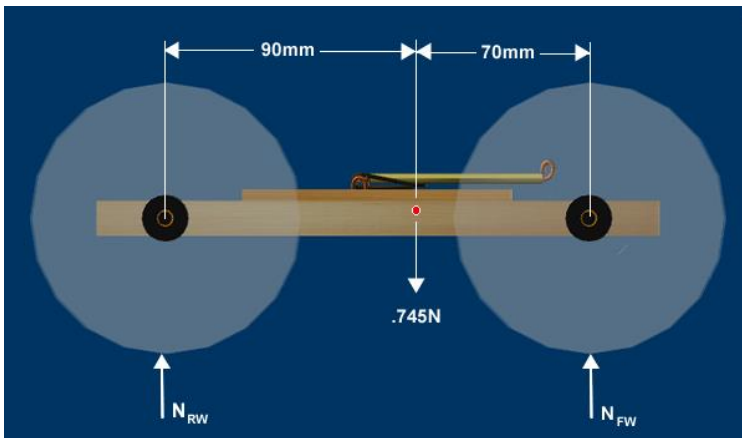
So, the key is to determine how the total weight of the car is distributed between the rear and front wheels. Once we know this, we can easily calculate our normal forces using the following formulas.

$$N_{rw} = k_{rw} W \quad \text{and} \quad N_{fw} = k_{fw} W$$

In these equations, the variable k_{rw} and k_{fw} simply represent the proportion of the car's weight carried by the front and rear wheels. These variables depend on the position of each set of wheels relative to the center of mass, and are calculated as follows.

$$k_{rw} = \left(1 - \frac{d_r}{d_r + d_f} \right) \quad \text{and} \quad k_{fw} = \left(1 - \frac{d_f}{d_r + d_f} \right)$$

These formulas are not as complicated as they look. What they basically say is that the wheels closest to the center of mass carry a higher proportion of the weight. Take a look at our illustration above. If we know the center of mass, we can calculate what seems intuitive. Let's give it a try.



Let's say our example car has a total mass of 76 grams, so the total weight can be calculated as follows. Remember to convert grams to kilograms!

$$W = mg = 0.076\text{kg} \times 9.81 \frac{\text{m}}{\text{s}^2} = 0.745\text{N}$$

Now we need to determine how much of this weight is carried by the front and rear wheels, so

$$k_{rw} = 1 - \left(\frac{90}{90 + 70} \right) = .44$$

and

$$k_{fw} = 1 - \left(\frac{70}{90 + 70} \right) = .56$$

In racing circles, this is called the vehicle's weight distribution. Multiply the results by 100 to convert to percentage and we find 44% of the weight is on the rear wheels and 56% is on the front.

Now that we know how the weight is distributed, we can easily calculate the normal forces at the front and rear wheels.

$$N_{rw} = k_{rw} W = .44 \times .75\text{N} = .33\text{N} \quad \text{and} \quad N_{fw} = k_{fw} W = .56 \times .75\text{N} = .42\text{N}$$

Wheel and Track Friction Force

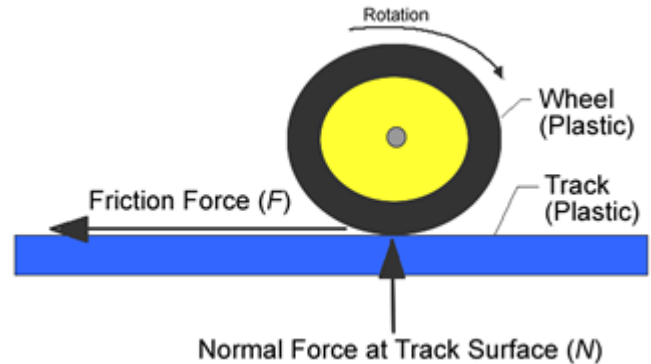
Now that the normal forces at the front and rear wheels are known, we can calculate friction forces that apply when the car is in motion. Using plastic CD/DVD wheels, the coefficient of friction (refer to table) between the rear wheel and race surface is 0.0035.

Therefore, the friction force on at the front wheel is:

$$F_{rw} = \mu N_{rw} = .0035 \times .33N = .0012N$$

Friction force of the rear wheel is:

$$F_{fw} = \mu N_{fw} = .0035 \times .42N = .0015N$$



Axle and Bearing Friction Force

For the axle and bearing, we need to subtract the weight of the wheels and axles since the bearings do not carry this load. Given 37g mass of the wheels (4 CD/DVD Wheels) and two brass tube axle assemblies of 9.2g, then subtracting the sum of their mass ($37g + 9.2g = 46.2g$) from the total mass of 76g we find that chassis mass is 29.8g ($76g - 46.2g = 29.8g$) or .03kg.

Now stepping through the equations as done above, we find the weight of the chassis by multiplying mass and gravity force.

$$W = .03kg \times 9.81ms^2 = .29N$$

The normal force at the front axle and bearing is:

$$N_{ra} = k_{ra}W = .44 \times .29N = .128N$$

and for the rear axle and bearing:

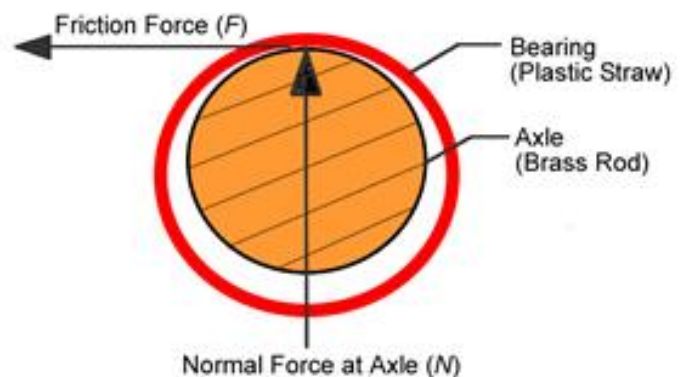
$$N_{fa} = k_{fa}W = .56 \times .29N = .162N$$

Looking at the table above, we find that the coefficient of friction for a brass axle on a plastic straw bearing surface is .04. Therefore, the friction force for the front is:

$$F_{ra} = \mu N_{ra} = .04 \times .128N = .00512N$$

and for the rear axle and bearing:

$$F_{fa} = \mu N_{fa} = .04 \times .162N = .0065N$$



Total Friction Force

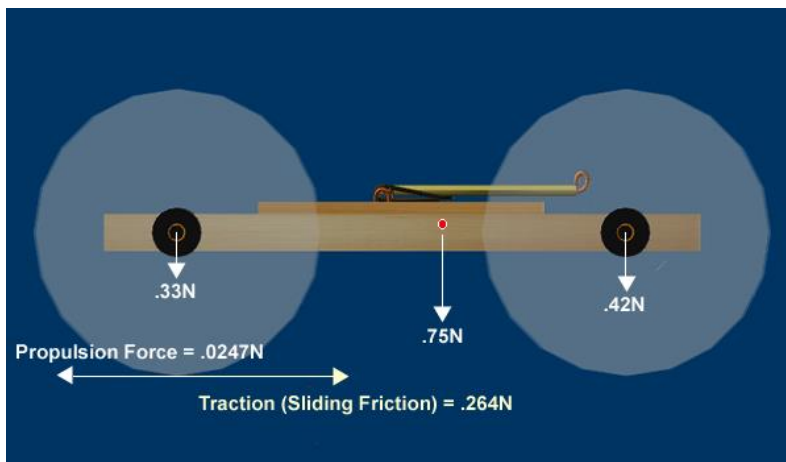
So what is the total force of friction working to slow the vehicle? Just add them up.

$$F_{tot} = .0012N + .0015N + .0051N + .0065N = .0143N$$

Remember this force is working against you. With a powertrain force of .039N, the net force is now $0.039N - 0.0143N = 0.0247N$. Not a large force but enough to start the car moving. When the power expires, the friction force takes over to slow the vehicle. Careful consideration of friction forces can mean the difference between first and second place.

Traction

Friction is needed to transfer the torque from the axle to force that moves the vehicle. **Too much tire and road friction will add unwanted negative force. Too little, and the tire will spin. Traction is the adhesive force that prevents sliding.** For the car to move, the traction force must be greater than the drive force.



Given the a sliding friction coefficient of 0.8 and a normal of force of 0.33N on the drive wheels, we have a traction force of 0.264N

$$F_{traction} = .8 \times .33N = .264N$$

In the previous section, net force propelling the vehicle was calculated to be 0.0247N.

$$.264N > .0247N$$

With traction force greater than propulsion force, we would expect the car to move without wheel slippage.

Solving for Distance and/or Speed

Now we know the mass of the vehicle, force produced by the powertrain, friction force, and the distance traveled under power. The engineering problem involves either maximizing distance traveled or speed (velocity) at a given distance (or both). To solve for distance and velocity, we can use the kinematic equations. The kinematic equations are four equations that describe an object's motion. We will utilize two of these equations to solve for velocity and distance. But first, it starts with Newton's 2nd Law of Motion.

$$a = \frac{F}{m}$$

As we learned in a previous lesson, the force of the spring is greatest when fully wound then decreases based on the spring constant. Working with an average force of .02N over the power duration, acceleration is equal to:

$$a = \frac{0.02N}{0.076kg} = 0.264 \frac{m}{s^2}$$

Velocity (Speed)

The kinematic equation for velocity is:

$$v_f^2 = v_i^2 + 2ad$$

We can use this to determine the velocity for a given distance (d). This includes the distance under power as calculated in the previous lesson or a given race distance such as 20 meters. Since initial velocity is zero ($v_i=0$) and using the distance under power (16.4m), we have:

$$v_f^2 = 2 \times 0.264 \frac{m}{s^2} \times 16.4m = 8.66 \frac{m^2}{s^2}$$

$$v_f = \sqrt{8.66 \frac{m^2}{s^2}} = 2.94 \frac{m}{s}$$

So, the vehicle in this example traveled 16.4 meters under power and reached a final velocity of 2.94 m/s.

It is important to point out that this estimate is only true if acceleration is constant - which its not. This is just an estimation to help understand the impact of different design choices. In reality, we need to calculate acceleration and velocity at lots of points along the pulling distance, which is what the simulation software does.

Time

We can use other kinematic equations to calculate the time to travel the pulling distance based on the final velocity. Using the equation:

$$t = \frac{v_f - v_i}{a}$$

With $v_f = 2.94$ m/s and $v_i = 0$, We have:

$$t = \frac{2.94 \frac{m}{s}}{0.264 \frac{m}{s^2}} = 11.14s$$

Distance

When powertrain force is exhausted, friction takes over and slows the vehicle to zero velocity. Using Newton's Second Law, the rate of deceleration (negative acceleration) is equal to the friction force divided by the mass.

$$a = \frac{0.0143N}{.076kg} = 0.19 \frac{m}{s^2}$$

The kinematic equation to solve for distance with final velocity equal to zero ($v_f = 0$) and initial velocity (v_i) of 2.94 m/s is:

$$d = \frac{v_i^2}{2 \times a}$$
$$d = \frac{(2.94 \frac{m}{s})^2}{2 \times 0.19 \frac{m}{s^2}} = 22.75m$$

The total distance traveled is the sum of the distance under power and distance decelerating.

$$\text{Total Distance} = 27.4m + 22.75m = 50.15m$$

As you can see, with the kinematic equations you can estimate the velocity of a vehicle over a given distance and the total distance.

Optimize

Optimization is a process to make a design as "perfect" as possible. To optimize a design, the process involves analyzing each part, component and sub-system to increase the performance or effectiveness of each. The result of optimization is an improved system. In this case, improvement in your Machine Racer performance.

1. **The first step is to identify the variables in the design that can be changed.** These are the parts that can be changed:

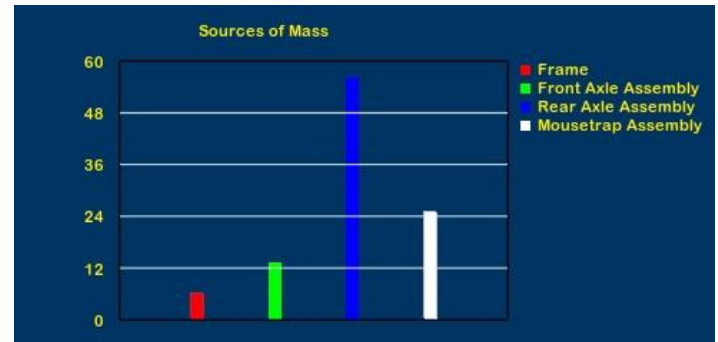
- spring location
- lever arm length
- axle diameter
- wheel diameter
- material/size (mass)
- bearing type/surface.

2. Measure the factors that can improve performance. For a Machine Racer design, these include sources of mass, sources of friction and powertrain (see graphs below).

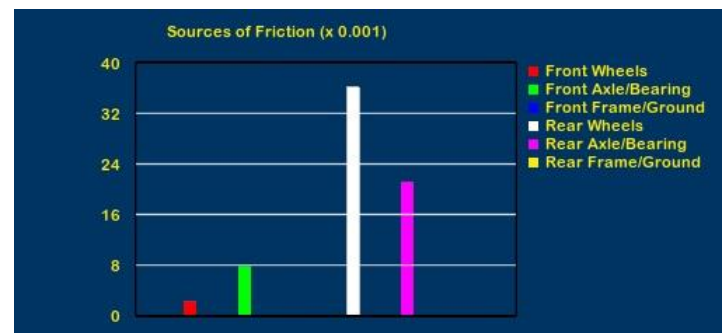
3. Analyze each variable to determine what can or should be improved.

4. **Make the recommended change(s) then test (virtual race) to see if the change has improved the system performance.**

Given Newton's 2nd Law, reducing the mass of the vehicle will increase acceleration. Given the sources of vehicle mass, is there a way to optimize acceleration by changing components?



Friction opposes propulsion force and affects coasting distance. Is there a way to reduce friction to optimize performance?



For the vehicle to move off the starting line, propulsion force must be greater than friction force. **Traction must be greater than propulsion force to prevent wheel spin.** However, an increase in traction is an increase in rolling friction. How can you optimize traction to minimize friction?

