

Newton's Laws and Friction

Friction is a Doubled Edge Sword

Description

This lesson introduces GEARS users to three related concepts, these are:

- 1.) The nature of forces
- 2.) Newton's laws of motion
- 3.) The force of Friction.

Forces act on objects causing them to move, speed up, slow down and stop. Forces can be thought of as pushing or pulling actions. When forces acting on an object are in balance, the object exhibits a steady rate of (relative) motion. When forces acting on an object are not balanced the "net" force causes objects to change their rate of motion or direction of motion. We call this change in the rate or direction of motion an acceleration.

Newton's fundamental law of motion is described by the relationship:

$$\text{Force} = \text{Mass} \times \text{Acceleration} \quad \text{or} \quad F = ma$$

The obvious implication of this simple algebraic statement is that the force required to change the motion of an object increases as the mass of the object increases.

Friction is a force that acts to oppose the motion of objects moving in contact with each other. Friction acts in opposition to forces that cause objects to move. The degree to which friction acts between objects is a function of the nature of the material, and the force with which the objects are held in contact.

Different combinations of materials exhibit different coefficients of friction. More simply, some materials slide against each other more easily than other materials. The ratio between the force holding two surfaces in contact with each other, and the force required to cause them to slide against each other is called the coefficient of friction.

Students who participate in this lesson will learn basic techniques for evaluating forces, motion caused by forces acting on objects and the effect of friction as a force that opposes motion.

Terms, Concepts, and Definitions

Kinematics	Dynamics	Force
Newton's First Law	Momentum	Friction
Newton's Second Law	Work	Static Friction
Newton's Third Law	Gravitational force	Sliding friction
Action-reaction forces	Weight	Coefficient of Friction
Inertia	Inertial mass	Acceleration of Gravity

Materials/Equipment/Supplies/Software

Pen/Pencil
Tape
Assorted Masses

Calculator
3-5 lb Spring scale
GEARS-IDS Kit

GEARS-IDS Robot
String
Long Table
Stop Watch

Objectives

The objectives of these lessons are to:

- Identify the nature of forces that act on objects
- Calculate Force and Weight
- Recognize and define terms associated with Forces and Friction.
- Measure the force of friction
- Calculate the coefficient of friction between two surfaces
- Use Newton's Laws to predict the effect of forces acting on objects.
- Develop design strategies that successfully resolve forces acting on a mechanism

Things to know before you start.

Students who participate in this lesson should review systems of units including SI, Imperial and MKS systems. In addition students should be familiar with using online conversion calculators like <http://www.onlineconversion.com/density.htm>

Familiarity with concepts involving motion, velocity and acceleration is helpful.

Participants should also be comfortable manipulating simple algebraic statements and understand the nature of vectors.

Mechanisms, Motion, Work and Friction

The term work is a useful concept. Work is the product of a force acting over a distance. The algebraic statement looks like this:

$$\text{Work} = \text{Force} \times \text{Distance}$$

Machines produce useful work by transforming energy from one form to another, or by changing the direction or magnitude of applied forces. For example, batteries convert chemical energy into electrical energy and internal combustion engines convert the heat of burning fuel into kinetic or moving energy.

Mechanisms are made to move by the application of forces.

Friction is a force that opposes motion and wastes energy. Some of the energy used to create the forces that move objects is also used to overcome oppositional forces due to friction. Friction reduces the efficiency of machines and mechanisms, and good designers are always looking for ways to minimize friction.

When mechanisms or objects in contact, move relative to one another frictional forces work in opposition to their relative motion.

The successful operation of any mechanism depends on the builder's ability to carefully and deliberately understand and optimize the desirable effects of forces and minimize or neutralize the undesirable forces acting on the mechanism being designed.

For example; The wings of an airplane must develop lifting forces capable of carrying a heavily loaded plane aloft, yet they must be strong enough to resist the shearing forces generated during take off and landing over a period of many years. Automobile fuel efficiency is improved by making cars lighter, but designers must also make cars strong enough to protect passengers in the event of accidents.

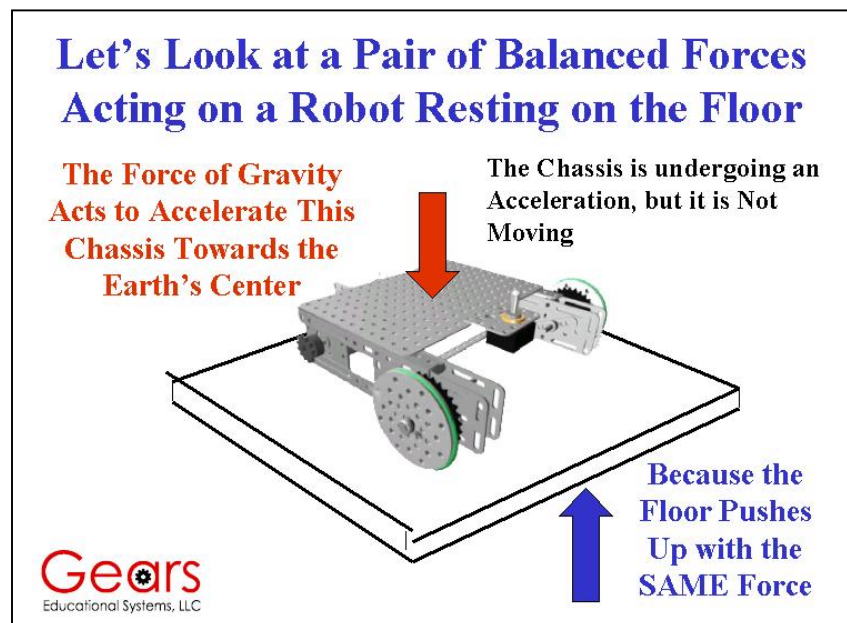
The ability to understand and resolve forces acting on a mechanism is an important part of the engineering design process and it begins with a thorough understanding of the basic concepts of force and motion.

Forces and Motion; Simple as 1,2,3.

When a net (unbalanced) force acts on an object to changes it's rate of motion or direction, the object accelerates. This change in motion can be either linear or circular.

A force is simply a push or a pull that causes an object to start moving, stop moving, or change the direction of its motion. When you place a GEARS robot on the floor, the force of gravity causes the robot to exert a force against the floor, the floor "Reacts by pushing up against the robot with an equal force. After all, if the floor pushed up with a force greater than the weight of the robot, the robot would begin to move upward, if

the force of the floor were less, the robot would sink downward. The result is a balance of forces acting on the robot and it does not move. Forces are vector quantities and vectors as we learned earlier have magnitude and direction.



Newton's Laws of Motion

Sir Isaac Newton, the famous scientist who studied the motion and acceleration of objects described the effect of forces on objects with three eloquent statements

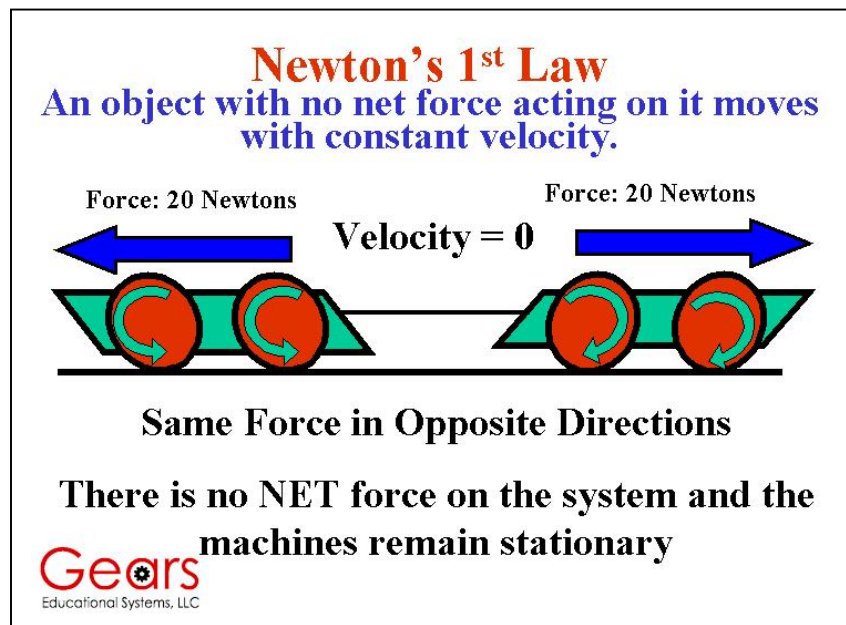
Newton's First Law: An object with no net force acting on it moves with constant velocity.

Note: An object at rest (not moving) has a constant velocity of 0 (zero). Newton's first law applies to both constant velocity (moving) objects and objects that are not moving.

Imagine two identical GEARS robots connected by a string and involved in a game of tug of war. Each robot has the same batteries, motors, gearing tires and the components are all placed in identical places (weight distribution is the same). Robot A pulls to the left and Robot B pulls in exactly the opposite direction to the right. Both robots will exert a pulling force on each other that will be transmitted through the cable. The cable, and the robots connected by the cable form a system. In this scenario, the system is in balance.

It is interesting to consider design factors that might allow a robot to pull harder in a game of tug of war. These could be;

- The battery amperage (current) drawn by each robot
- The power (rpm and torque) of the motors
- The size of the wheels
- The coefficient of friction between the wheels and the surface
- The weight of the robots
- The frictional efficiency of the bearing surfaces employed in the robot



Newton's Second Law: The acceleration of a body is directly proportional to the net force acting on it and inversely proportional to its mass.

If Robot A were to optimize its design for traction and put more of its weight over the point of contact of the tires, it will increase the frictional coefficient between the tires and the surface and likely develop a stronger pulling force. In this case robot A will pull with greater force in the left direction and the forces acting on this system will be unbalanced. There will be a negative (left) net force acting on the system causing the robots and string to move (accelerate) left.

The robots and string system will accelerate left at a rate that is proportional to the net force acting on the system.

A simple algebraic statement can describe the relationship between force, mass and acceleration,

$$\text{force} = \text{mass times acceleration} \quad \text{or} \quad \mathbf{F = ma}$$

Acceleration and Force are vectors; they contain both direction and magnitude. If an unbalanced or net force acts upon an object, the object will accelerate in the direction of the net force at a rate proportional to the net force.

F= ma describes an important relationship between an object's mass and the force required to cause the object to accelerate. This relationship has important implications for mechanical designers: If you want to accelerate a given mass more quickly, you will have to use proportionally greater force. In order to increase the acceleration of a given mass, significantly more energy is required. The energy sources stored on board a robot or radio controlled machine are limited by the electrical energy stored in the battery and the pressurized air stored in the pneumatic reservoir.

An understanding of Newton's second law will provide designers insights that will suggest successful and effective ways to manage the on board energy resources and forces generated by the mechanisms they create.

Calculating Forces

When we calculate force(s) acting on an object, a new unit is produced, that unit is called a Newton (N). This unit is appropriately named after Isaac Newton. 1 Newton is the force required to accelerate a 1 kilogram mass at a rate of 1 meter per second/ per second.

This means that a one Newton force will cause a 1 kg mass to be moving at a rate of 1 meter per second at the end of 1 second of acceleration. At the end of 2 seconds the 1 kg mass will be traveling at 2 meters per second. Can you see the pattern? Expresses algebraically it looks like this:

$$\text{Velocity} = \text{Acceleration} \times \text{Time}$$

Example of Newton's Second Law :

The following example uses mixed units. Students should become accustomed to recognizing and reconciling units and measurement systems. Always identify and convert **all** the units in a given problem to the **same system** before beginning the to solve the problem. In this example we will convert lbs to kg and use the MKS system. A convenient source of online conversions is <http://www.onlineconversion.com/>

Find the Net Force that would accelerate a GEARS robot with a mass of 11 lbs at a rate of +4 m/s².

Define the variable:

m = 5 kg or 11 lbs. (1lb = .454 kg)

a = 4 m/s²

F = F ?

F = ma

F = (5)(2.1)

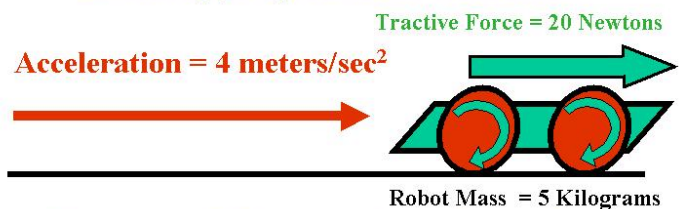
F = +20 Newtons

Note: The object will move in a positive direction, because a is +

Forces act in positive and negative directions

Newton's 2nd Law

The acceleration of a body is directly proportional to the net force acting on it and inversely proportional to its mass.



Force = Mass x Acceleration

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$$20\text{N} = 5\text{kg} \times 4\text{m/s}^2$$

Newton's Third Law: When one object exerts a force on a second object, the second exerts a force on the first that is equal in magnitude but opposite in direction.

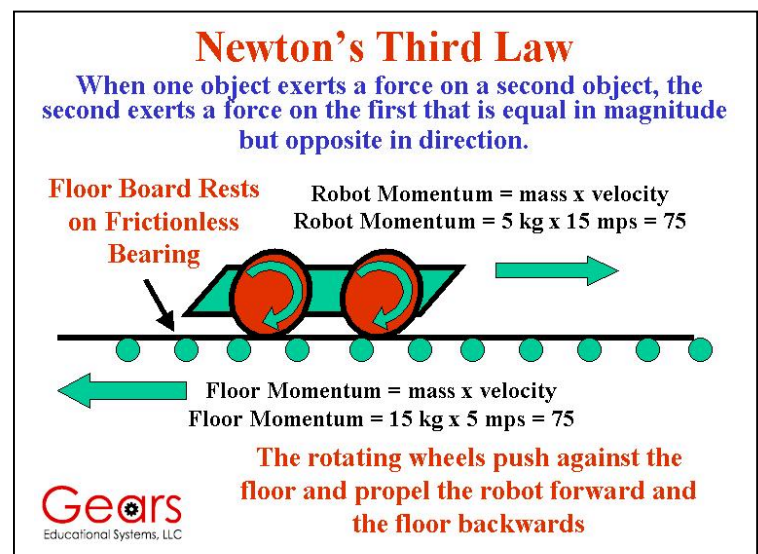
Simply put "You can't push on anything without that thing pushing back with an equal amount of force".

Newton's third law is also called the law of conservation of momentum. Momentum is a measure of the propulsive force of a moving object.

$$M \text{ (momentum)} = m \text{ (mass)} \times v \text{ (velocity)}$$

This has implications for the structural design of mechanisms. Engineers who design earthmoving equipment need to be certain that the machines they design can withstand the tremendous forces they generate in moving large amounts of earth!

These forces are called action-reaction forces. As we discussed earlier a GEARS Robot sitting on the floor exerts a force on the floor equal to the force the floor is exerting on the GEARS robot. In like manner, a robot that is pushing on another robot receives the same force that it exerts.



The competitive mechanisms you design need to have strong rigid structures to support the motors, sprockets and axles that generate the required forces to accelerate the robot components and mechanisms.

The Difference Between Mass and Weight

Weight

The weight of an object is the force we feel when we hold an object in our hand. The weight of an object is a function of the total gravitational force acting on the matter (stuff) of which the object is made. Here on the surface of the earth the force of gravity is relatively constant. Gravity pulls all matter towards the earth's center at a rate that is relatively constant over the face of the earth.

Out in space, far from any planets or stars, there is almost zero gravity. Therefore there is no force acting on the mass of an object. An object in space does not "fall" anywhere. You could place a bathroom scale under it, beside it, or on top of it and it would not register any weight. But it is still made up of matter (stuff).

Matter is independent of weight. An object can have matter but no weight...however it cannot have weight and no matter! Think about this.

Mass

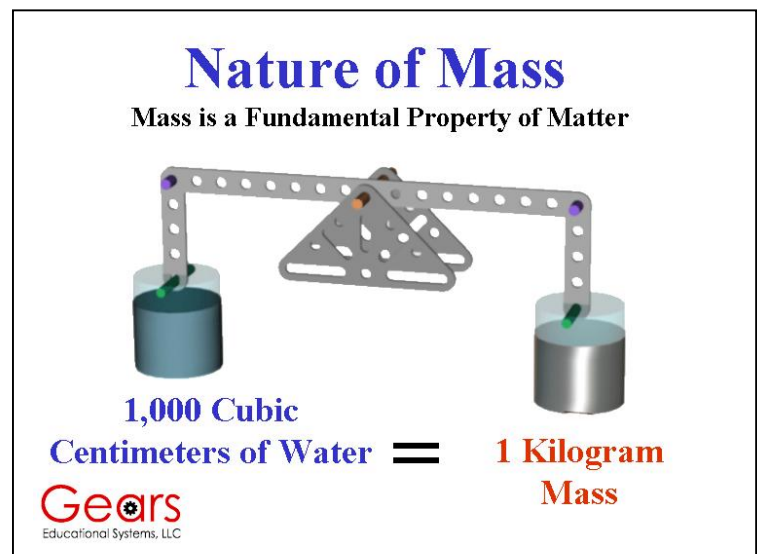
Mass is the quantity of matter (or stuff) the object contains. Everything is made up of particles (atoms and molecules), which in turn are made up of protons, neutrons and electrons.

A convenient unit of mass is the kilogram. The kilogram is defined as the amount of mass contained in 1000 cubic centimeters of water. By using a balance scale we can compare the masses of different objects to an accepted and universal standard of mass.

Mass is a fundamental property of matter. All matter is made of a variety of sub atomic particles such as protons neutrons and electrons. All matter exhibits the tendency to attract matter. This attractive force is called gravity. Gravity is the weakest of the 4 natural forces, but because all mass has gravity, and the earth is so massive, the force of gravity on earth is quite noticeable.

Remember that forces cause objects to accelerate: $F = ma$.

Gravity is a force and it causes all objects on earth to accelerate towards each other at a rate that is relative to their mass. The earth is very massive, and it causes all objects on it to accelerate towards the center of the earth at a rate of 9.8 meters/sec^2



Weight is the Result of the Force of Gravity Accelerating a Given Mass Toward the Center of the Earth.

Finding weight is simply applying the algebraic statement that describes Newton's second law:

$$f = ma$$

or in terms of weight and gravity, it is Weight = Mass times acceleration due to gravity or:

$$W = mg$$

Where W equals weight in Newtons, m equals mass in kilograms and g equals the acceleration of gravity which is 9.8 m/s^2 .

$W = mg$ is really another way of saying $F = ma$

Gravity and Mass

When we place a 1 kilogram (kg) mass on a metric scale we read the weight as....1 kilogram. The prefix kilo means 1000. The 1 kilogram object has a mass of one thousand grams.

The weight and the mass are the same under earth's gravity. But what force is being exerted by the acceleration of gravity acting on the 1 kg mass?

Force in the SI system is measured in Newtons. If you hold a 1 kilogram mass in your hand, the force you feel is 9.8 Newtons. This force is the result of the acceleration of gravity acting on the 1 kilogram mass in your hand. In order to hold the mass steady, you must push up with your arm and hand with a force of 9.8 Newtons.

If you held a 2 kilogram mass in your hand, you would need to push up with a force of 19.6 Newtons. If it were a 3 kilogram mass you would have to exert a force of 29.4 Newtons. Can you see the pattern? The relationship between the weight (force) of an object due to gravity and the mass of the object looks like this:

$$W=mg$$

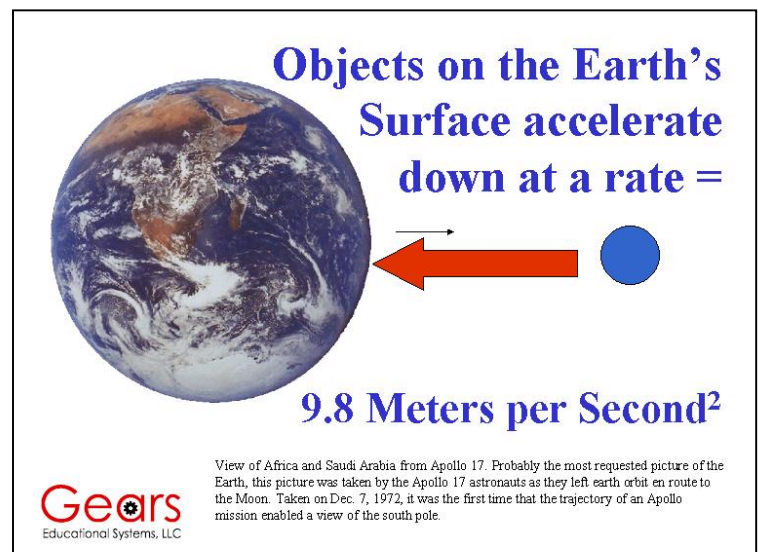
W= Weight (force) in Newtons

M= Mass in kg (Remember to use Kilograms not grams or ounces or pounds)

G= Acceleration due to gravity (9.8 meters/sec²)

The force of gravity is the same for each and every individual particle that makes up an object. Therefore each and every particle undergoes the same rate of acceleration towards the center of the earth. However, the force that each particle exerts as a result of this acceleration is multiplied the number of particles, or the mass of the object. More massive objects are accelerated towards the center of the earth at the **same rate** as less massive objects but more massive objects exert **more force** than a less massive object as a result of their greater mass times the acceleration of gravity.

This explains why larger rocks are more difficult to pick up than smaller rocks, but all rocks, and for that matter all objects fall towards the earth's center at the same rate!



Friction: A Resistive Force That Prevents Objects from Sliding Freely Against Each Other

Take the battery supplied with the GEARS-IDS kit, tie a string securely around it and drag it along the floor. You must apply a force on the battery to move it from one point to another. The greater the force you apply, the faster the battery will accelerate ($f=ma$)

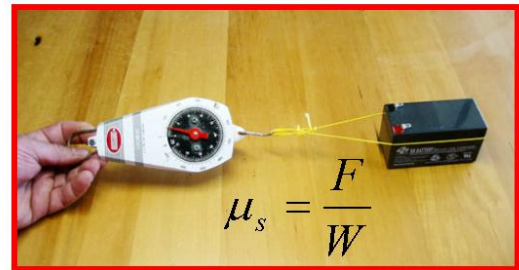
When you cease to exert a pulling force on the string, the battery comes to a rest. Some force must be acting in opposition to the force you apply to cause the battery to move.

One of the forces is friction. Friction acts in opposition to the force that moves (accelerates) the battery.

Friction is a double-edged sword. It can be desirable or undesirable depending on the mechanical functionality you are trying to optimize. The same frictional forces that cause unacceptably high mileage in automobiles also serve to stop cars safely.

The friction between the tires and the surface they are on allow a wheeled robot to generate tractive (pulling or pushing) forces, but these same forces cause energy loss while the robot is moving. Friction is a fact of life and there are times when we want to maximize friction and at other times we will want to minimize friction. Understanding how to do this requires an understanding of friction, and the causes of friction.

Using the Gears-IDS Battery to Calculate The μ_s Static



Coefficient of Friction

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4 Kinds of Friction

Static Coefficient The Force required to an object sliding across another is usually greater than the force required to keep them moving. Static friction is the force that holds back a stationary object up to the point that it just starts moving. The static coefficient of friction is the force that restricts the sliding movement of an object that is stationary on a relatively smooth, hard surface.

You can demonstrate this using the battery supplied with the GEARS-IDS kit. Attach 1 kg spring scale, or an equivalent Imperial scale of approximately 2 lbs, to a string attached to the battery. Slowly pull on the scale and drag the battery across a smooth surface. Note that the force required to start the battery moving is greater than the force required to keep it moving.

Kinetic coefficient Once you overcome static friction, kinetic friction is the force holding back regular motion. This, kinetic friction coefficient of friction is one of the forces restricting the movement of an object that is sliding on a relatively smooth, hard surface.

Deformation Coefficient

The deformation coefficient of friction is another force that restricts the movement of an object that is sliding or rolling across another surface that is relatively soft and deformed by the contact forces. An example might be the frictional forces developed by dragging the battery across a carpeted surface. In this case force must be applied to bend and deform the carpet pile ahead of the moving battery.

Molecular Coefficient

Molecular coefficient of friction concerns the force restricting the movement of an object that is sliding on an extremely smooth surface or where a fluid is involved. This is exemplified by oiled bearing surfaces, where the two materials are separated by a lubricant. Another example is that of an airplane moving through air, or a submarine moving underwater.

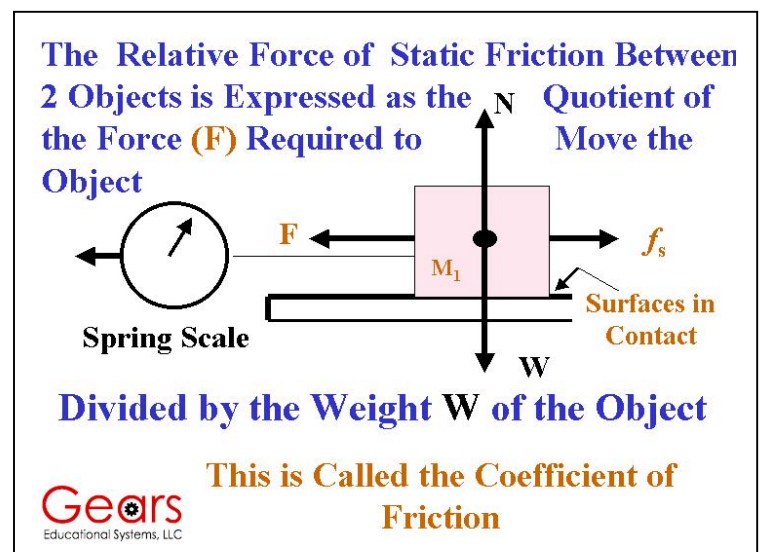
The Coefficient of Static Friction

The Coefficient of Static Friction is defined as the quotient obtained by dividing the value of the maximum force necessary to start one body moving over another.

The coefficient of friction is represented by the Greek letter μ (Mu)

The algebraic statement looks like this:

$$\mu_s = \frac{F_r}{F_n}$$



Where:

μ_s = Coefficient of Friction

F_r = Max Force required to start an object moving

F_n = Force normal, or the perpendicular weight of an object acting on a surface

The coefficient of friction is different for different materials. Try dragging the Gears battery across different materials including plastic, wood, steel etc. Do you get different readings on the scale? Does this result in different frictional co-efficient for each material combination?

Frictional coefficients for different materials are widely published. Look them up, and check them against your results.

What are the Implications For Machine Traction?

Study the formula for the coefficient of friction. Identify the two factors that affect friction.

These are:

- 1.) The type of materials that slide against each other greatly affect the frictional forces created. It takes greater force to slide rubber over wood than to slide steel over wood.. (Assuming that the forces pressing the materials together are the same) This is one reason why athletic shoes have rubber soles
- 2.) The perpendicular force acting to press the two materials together. This is called the normal force or force normal.

Question: How can you increase your robot's tractive forces given that you have the same materials?

Answer: Carefully design your robot in such a way that most of the robot's weight is directly over the point of contact between the wheels and the surface is a good start!

Activities

Force Activity: Building Newtons Cart

Download the Newton's Cart .pdf file from the **Learning Tools** section of this lesson. Build the Newton's Cart apparatus and perform the experiments described in the document. The objective of the activity is to provide students with an experiential understanding of the relationship between force, mass and acceleration.

Friction Activity: Sliding Batteries

Download the Friction slide show file from the **Learning Tools** section of this lesson. After reviewing the slide show, download the Calculating the Coefficient of Friction worksheet from the Learning Tools Section and perform the experiments described in the document. The objective of this activity is to provide students with an experiential understanding of the relationship between frictional forces, the nature of the materials in contact and the magnitude of the forces holding the materials in contact.

Worksheets

The Difference Between Mass and Weight

Download the Difference Between Mass and Weight .pdf file in the **Learning Tools** section of this lesson. This exercise helps students understand that weight is the result of gravitational forces acting on the mass of objects. Weight can be expressed as a force in units called Newtons. The objective of this exercise is to help students internalize concepts of force and mass as well as obtaining the ability to calculate force in Newtons.