HOW-TO GUIDE

The Use of Physical Models and Demonstrations in Engineering Education

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CONSTRUCTION

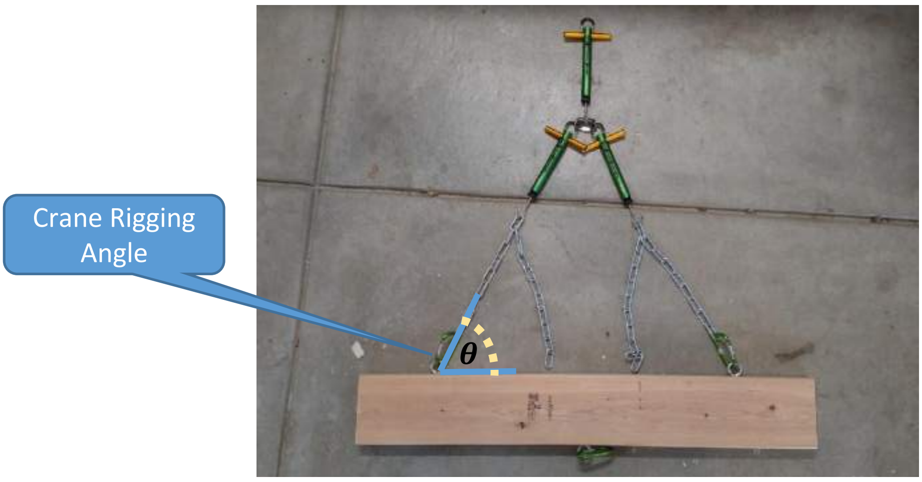
CRANE RIGGING ANGLES

CONSTRUCTION

Keywords: Angle, Crane Pick, Force, Lift, Load, Vector

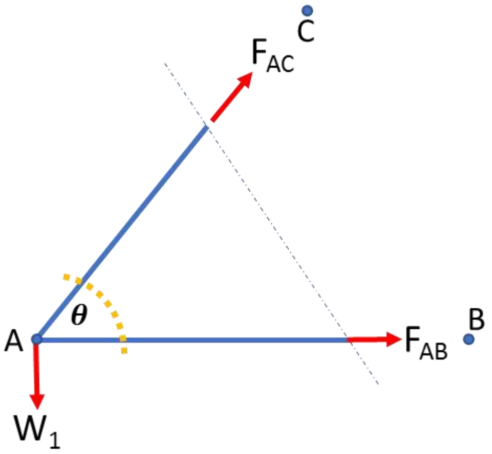
Submitted by: David Flaherty and Matt Morris

Model Description: This demonstration depicts the importance of rigging angles during crane lift operations on a construction site. Reducing rigging angles results in a significant amplification of forces in the rigging, potentially ***leading to failure***. By varying the connection points and sling length, students will be able to calculate the predicted forces and analyze the best combination of connection points and sling lengths to successfully complete the critical lift. The demonstration should take 15-20 minutes.



Engineering Principle: A sling's working load limit (WLL) is based on a crane lift performed at a straight (90°) angle. The forces in rigging (sling, chain, wire rope, webbing, shackles, etc.) increase substantially as the angle formed by the sling leg and the horizontal becomes smaller. The following chart shows the increased force applied to the rigging when the rigging angle is reduced. The key engineering principle with this demonstration is related to an understanding of statics. Students must comprehend that decreasing the angle creates a horizontal force component that in turn increases the tension in the rigging. This can be derived using the figure below.

F_{load}	Angle (θ)	F_{sling}	% of F_{load}
1.0	90 deg	1.0	100%
1.0	60 deg	1.2	115%
1.0	45 deg	1.4	141%
1.0	30 deg	2.0	200%
1.0	20 deg	2.9	292%
1.0	10 deg	5.8	576%



$+\uparrow \sum F_y = -W_1 + \sin(\theta) * F_{AC} = 0$, where $F_{AC} = F_{sling}$ and $W_1 = F_{load}$

$F_{sling} = \frac{F_{load}}{\sin(\theta)}$; for reference, $F_{load} = {}^{1}/_{2}\, F_{lift}$

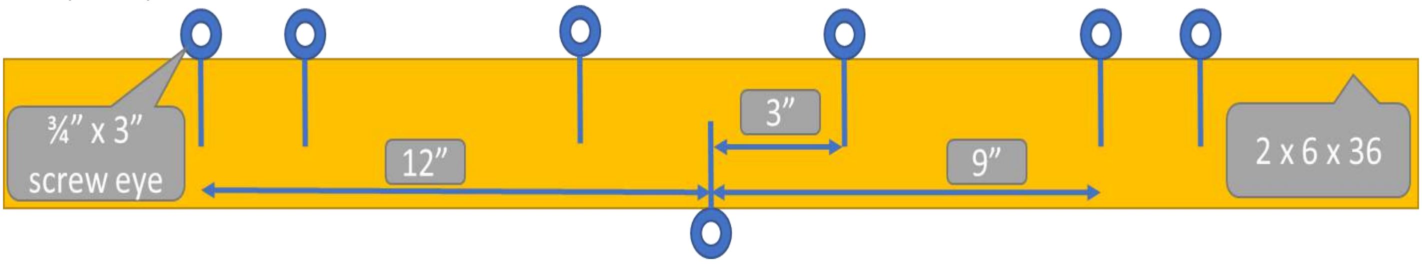
While increasing the connection angle of a two-point lift may be required to increase the stability of the lift, careful consideration must be taken in regards to the sling capacity and weight of the lift.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
3/16 in Chain	2x 2 ft sections	$8 at $2 per foot.	These represent the sling for the lift.
Twist Link Chain	1 foot	$1.50	This is smaller than the straight chain and is used to connect the weight plate to the spring link on the lower screw eye.
2x6 x 3 feet	1	$6; 20 minutes	Most pieces come in 8 foot sections. Once cut to size, this is the critical lift.
3/4 in x 3 in Screw Eyes	7	$5 at $1.25 per 2 pack	These are used for the rigging connection points on top and the load connection point on the bottom. 130-pound capacity.
3/16 in quick link	1	$2.25	This locks and holds the two spring scales along each chain. It also is used for the top spring scale to analyze the total weight of the lift. 450-pound capacity.
3 in spring link	3	$1 each	These are used for quick connections of the chains to the screw eyes and the weight to the load screw eye. 150-pound capacity.
20-lb spring scale	3	$11.50 each	These scales measure the weight of the lift and along each chain.
10-lb weight plate	1	$11	This increases the weight of the critical lift.

APPLICATION

Before Class: Build and verify your model. The imperfect connections at the screw eyes and the variation in the spring scale as a load is applied make predicting the exact angle difficult. The placement of the screw eyes and the length of the chain are intended to replicate scenarios with the connections at 30°, 45°, and 60°.



After cutting the 2x6 to 3ft. length, install the screw eyes along the centerline at the distances shown above. To ensure the spring scale hook remains centered during the lift (and creates an equal force in both scales), use wire or duct tape to prevent its movement. Display the 2x6 at the front of the class, but do not have anything connected to it. Let the students build their answer as they work to solve the problem.

<u>In Class</u>: The scenario is as follows; the students are new project engineers on a job site. The project manager is out sick and leaves them in charge for the day. The easy day gets complicated when the crane operator insists on executing the project's critical crane lift on short notice due to impending weather. However, due to the unscheduled nature of the request, the project engineer is unsure if the slings on hand are capable of safely executing the lift. The project engineer tells the crew that the crane lift will happen in 15 minutes, which buys some time. The project engineer runs back to the trailer to calculate how to use the two (2) 11-ton slings to lift the 15 to 16-ton object worth $2 million. The object has only three "picking eyes" on each side to maintain its balance. The crane operator recommended the connections farthest from the center to help with stability.

Theory: Given the fixed connection options, have the students calculate the tensile forces in the sling using the farthest connection (12 inches from center). Ask them what angle they would recommend if they didn't have time for calculations, and why? By adjusting the basic equation to $F_{sling} = \frac{F_{load}}{sin(\theta)}$, the students can calculate the tension in the sling at any angle. If the students are using their computers, remind them of the need to convert the answer to degrees from radians if their output is not making sense to them.

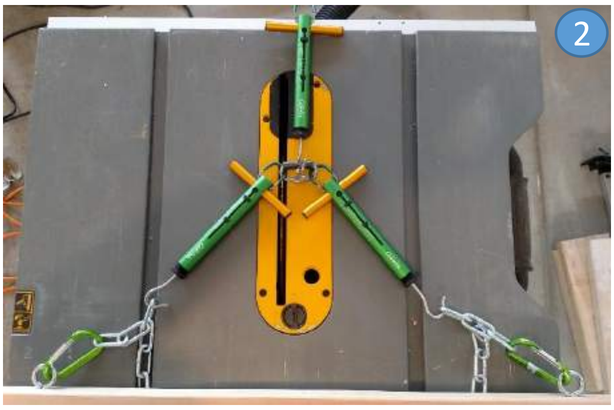
Example: The total weight of the demonstration should be 15-16 pounds. Explain to the students that they could use trigonometry to calculate the required sling lengths given the fixed connection points and desired connection angles. However, the variation in this model makes it difficult to perfectly replicate such detailed specifics. As the spring scales extend to register the weight, they alter the length of the cable and therefore the angle at the connection and the resulting tension within the cable. Calculations that include spring deflection yield the following cable length *approximations* to get the desired connection angles: 30° (no chain, but chain must hang from connection for consistent weight) 1, 45° (3 links) 2, and 60° (9 links). These numbers only apply when analyzing the connection that is 12 inches from center. Ask for four volunteers (1 on each side of the lift, 1 to make the connections and document the results, and 1 to hold the top scale when the lift is tested). Test the model at the approximate angle the students chose as the way they would conduct the lift. Then, conduct the connections described above for 30°, 45°, and 60°. Lastly, ask the students to create the worst-case scenario for the rigging and test that example as well. By keeping the lift symmetrical, the weight of the lift can be divided by two and analysis conducted on half of the rigging that creates a right triangle. Given F_{sling} and F_{load} of each documented test, have the students calculate the actual angles by adjusting the basic equation to $\theta = \sin^{-1}\left(\frac{F_{load}}{F_{sling}}\right) / \frac{\pi}{180}$. Dividing by $\frac{\pi}{180}$ converts the answer from radians to degrees.

The following chart compares theoretical angles based on perfect trigonometry to the test angles calculated from the resultant forces under varying load connections.

L_{sling}	Expected Angle (θ)	F_{sling}	F_{load}	Test Angle (θ)
No chains	30.0 deg	15.0	7.5	30.0 deg
3 links	45.0 deg	11.8	7.5	39.5 deg
9 links	60.0 deg	9.0	7.5	56.4 deg

As shown above, the angles are not always perfect matches, but are close enough to effectively highlight the amplification of forces in the sling based on rigging angles. Notice the applied force on the sling exceeds its 11lb capacity at 45 degrees!

Finally, ask the students if they have ever heard of the American Death Triangle. If a student has, have them explain its meaning to the class. This refers to a common source of fatalities in rock climbing and the principles are quite similar to equipment rigging.



Additional Application: This makes for a good discussion on Factors of Safety. Ask the students about their tolerance for safety and how close to the sling's capacity would they execute the lift. Did they inspect the slings? The sling's rating is accurate when it leaves the manufacturer, but how have they been maintained? Are they rusty, worn, or frayed?

It is entirely possible that a foreman or superintendent does not recognize the implications of different rigging angles. Focus on emphasizing the importance of being able to say "No" to unexpected job site suggestions as a young engineer. Safety should drive the schedule.

This gives an opportunity to discuss other rigging arrangements such as the use of a spreader bar.

Talk about real world examples where critical lifts did not go as planned and discuss the serious implications about the failures. This is a great time to include a PowerPoint slideshow with pictures of failed crane lifts.

EXCAVATION AND EARTHWORK PRESSURE

CONSTRUCTION

Keywords: Equilibrium, Pressure, Shoring, Soil

Submitted by: Dr. Matthew Hallowell

Model Description: This in-class activity provides students the opportunity to participate in an interactive demonstration to visualize the concepts of soil pressure and potential effects on construction excavation support systems. In this demo, students are able to interact directly with small-scale models to exhibit the concepts of at rest (equilibrium) soil conditions, active soil pressure, and passive soil pressure. This demonstration should take 10 minutes.

Engineering Principle: The overall objectives of this demonstration focus on the concepts of soil pressure and potential interactions with construction excavation support systems. Multiple soil pressure conditions can be seen throughout the different stages of the demonstration, including at rest condition (equilibrium), active soil pressure, and passive soil pressure. Through these pressure conditions, students are able to witness the concepts of pressure first hand, while also providing visualizations of the plane of soil failure and effects on earth support systems. The concept of soil pressure is essential within construction engineering; as a proper understanding of soil behavior is necessary for the design and construction of excavation support systems on a large scale.

At its original state, the model exhibits the 'at rest' soil pressure condition, meaning the horizontal and vertical pressures of the earth are at equilibrium. The action of excavation removes internal stress along one plane, resulting in an imbalance of pressure within the system. This imbalance of stress causes an increased application of pressure on the excavation support system, which in turn counteracts the pressures and restricts the soil from collapsing towards the direction of least resistance.

The excavation support system is able to resist the increases in pressure until slight failure or movement of the wall occurs. This condition, known as active pressure, occurs when the increases in soil pressure reaches a point of failure within the support system. In instances of active soil pressure, the natural pressure of the soil is much less than at rest conditions, as a portion of the horizontal stress is dissipated through the movement of soil thus moving it closer to the natural failure plane.

Passive soil pressure occurs when the pressure of soil reaches a point of failure of the support system, which in turn causes shear failure in the soil. Much greater amounts of passive pressure are required to reach failure when compared to active pressure, as the internal stresses (i.e. weight of soil above) must be overcome before movement can occur.

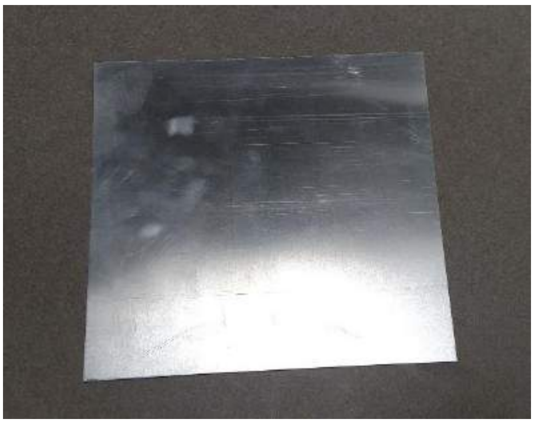
In this circumstance, the soil is passively pushed until slippage occurs along the natural plane.

$$Active\ Soil\ Pressure:\ K_a = tan^2\left(45 - \frac{\phi}{2}\right)$$

$$Passive\ Soil\ Pressure:\ K_p = tan^2\left(45 + \frac{\phi}{2}\right)$$

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Plastic Containers (size of shoebox)	4 students per group	$30 each for the example dimensions	Containers serve as the boundary for the contents of the demonstration
Sand	1 bag	$5	Sand is used to represent soil/earth
Aluminum / Metal	1 sheet per ox	$2-15; 30 mins	The metal represents the in-ground excavation support system. Cut the material to match the interior dimensions of the box.



APPLICATION

Before Class: Acquire demonstration materials. Assemble demo kits by filling plastic containers approximately half full with sand. Insert a piece of aluminum foil in the middle of the demo, ensuring the height of the support system is greater than the height of the sand material. Fill container with remainder of desired sand amount on opposite side of aluminum wall.

In Class: Start the demonstration by dividing participants into groups of four or less. After the groups have been divided, instruct students to begin transferring the sand from one side of the excavation support system to the opposite site. This step represents the actual excavation of earth in construction. Repeat the process of excavating materials until the effects of pressure can be seen on the support wall i.e. when the excavation support system, which is sheet pile in this case, fails. The movement of soil will eventually lead to conditions of active pressure, passive pressure, and shear failure. The model will allow students to feel the pressures on the aluminum sheet and understand how forces act on a sheet pile.

DYNAMICS

WHEN WORLDS COLLIDE

DYNAMICS

Keywords: Collision, Deformation, Rebound Velocity, Restitution

Submitted by: Charles Packard

Model Description: This is a simple demonstration of the phases of a collision for central impact. Two squeeze balls are used to show the phases. 1 This demonstration should take 3-5 minutes.

Engineering Principle: Two objects in a head-on or rear-end collision ("central impact") will deform as they collide. At the time of maximum deformation, they will have reached the same velocity. The period of deformation will typically be followed by a period of restitution, at the end of which the two objects will either have regained their original shapes or will have retained some degree of permanent deformation.

REQUIRED ITEMS

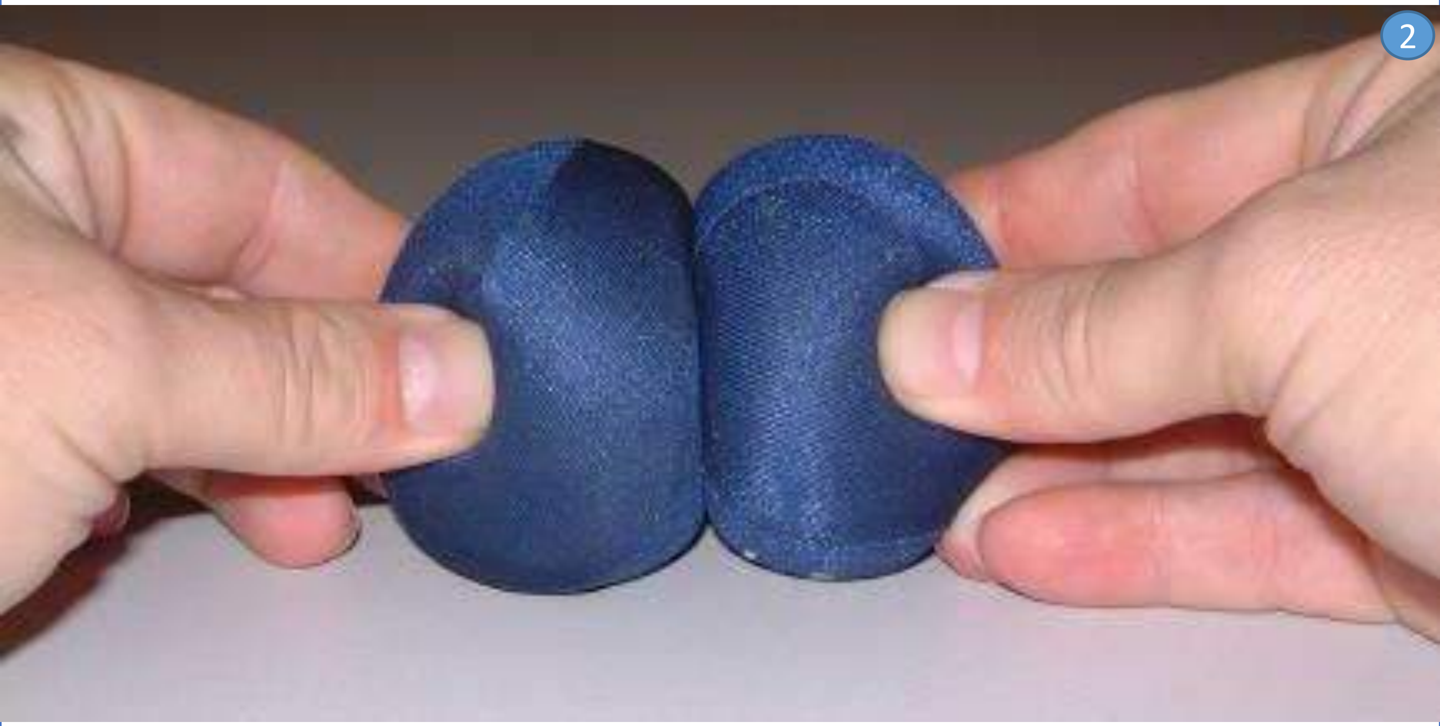
Item	Qty	Cost and Build Time	Description/Details
Squeeze or Stress Balls	2	$10 for a pair	Small, hand sized balls which yield when squeezed, yet don't permanently deform can be obtained from sport stores or pharmacies for low cost.

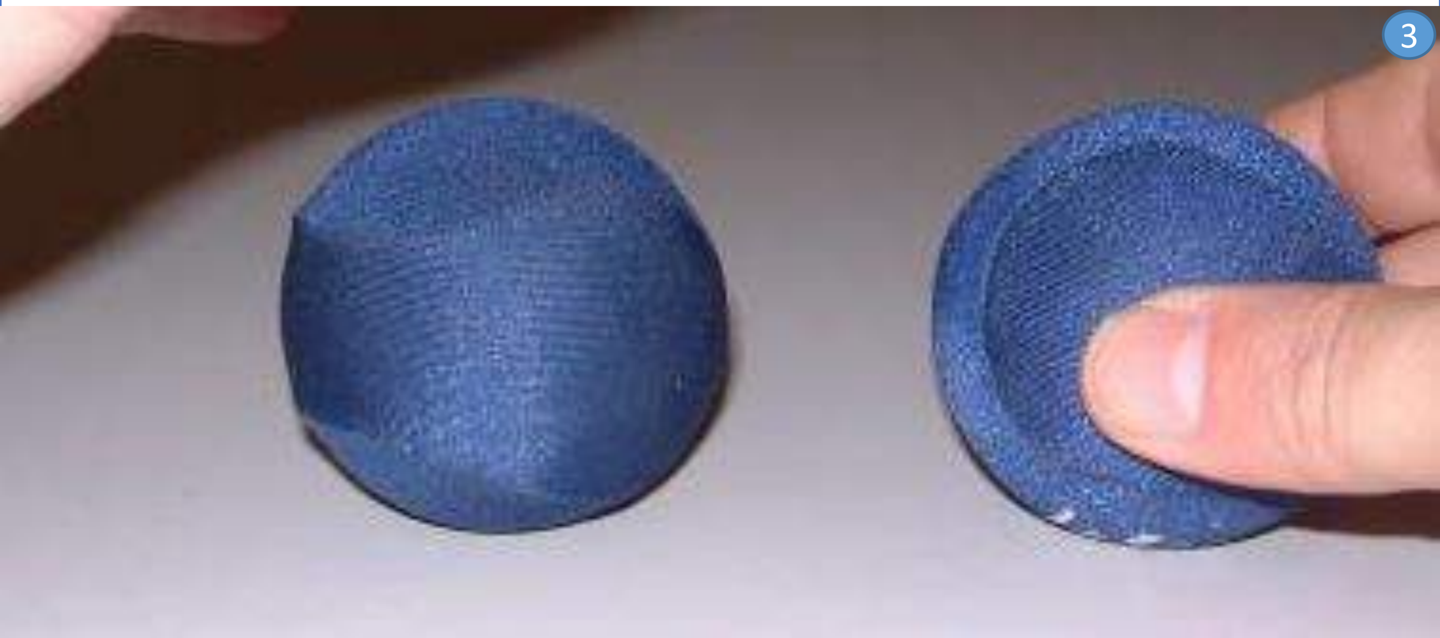
APPLICATION

Before Class: Practice the demonstration.

In Class: Discuss the phases of a collision and show these phases with the squeeze balls.

Observations: The students should observe that the balls start to deform upon contact, that there is a finite period of time during which both balls deform, and that there is also a finite period during which the balls return to their original respective shapes (the deformation and restitution periods are not necessarily of the same duration). 2 Students should also recognize that a force exists between the balls once they start to deform. This force can be demonstrated by rapidly releasing one ball while the other one is held stationary—the released ball rolls rapidly away from the one held stationary. 3





Additional Application: Two clay balls of roughly the same diameter as the squeeze balls could also be used to emphasize that the period of restitution need not equal the period of deformation. Follow the same procedure as before, pressing the balls slowly together, then releasing one while holding the other. The period of restitution is clearly smaller than the period of deformation. Next, drop a clay ball on the floor along with a ping-pong ball, to show what happens in terms of rebound velocity. Ask what happened to the earth during the collision, and why the rebound speed never equals that of the speed just before impact.

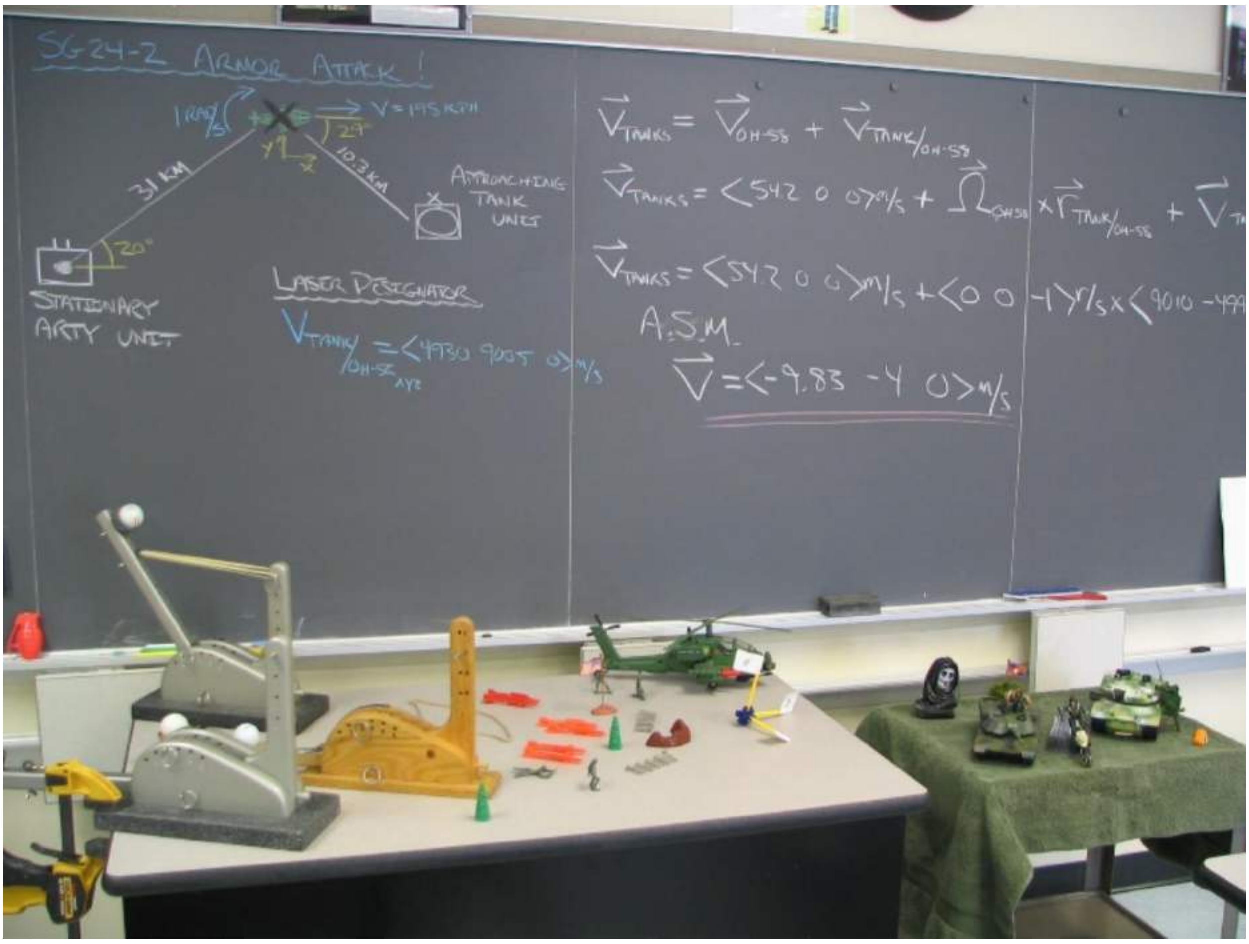
ARMOR ATTACK

DYNAMICS

Keywords: Absolute Velocity, General Planar Motion

Submitted by: Tom Messervey

Model Description: This training aid demonstrates a practical application of the kinematic relationships for a translating and rotating frame of reference. This demonstration should take 10-15 minutes.



Engineering Principle: This lesson is an application of the previously developed vector equations for velocity and acceleration in a translating and rotating frame of reference.

$$v_b = v_a + v_{b/a}$$

$$v_b = v_a + \Omega \times r_{b/a} + (v_{v/a})_{\mathrm{xyz}}$$

$$a_b = a_a + a_{b/a}$$

$$a_b = a_a + \dot{\Omega} \times r_{b/a} + \Omega \times (\Omega \times r_{b/a}) + 2\Omega \times (v_{b/a})_{\mathrm{xyz}} + (a_{b/a})_{\mathrm{xyz}}$$

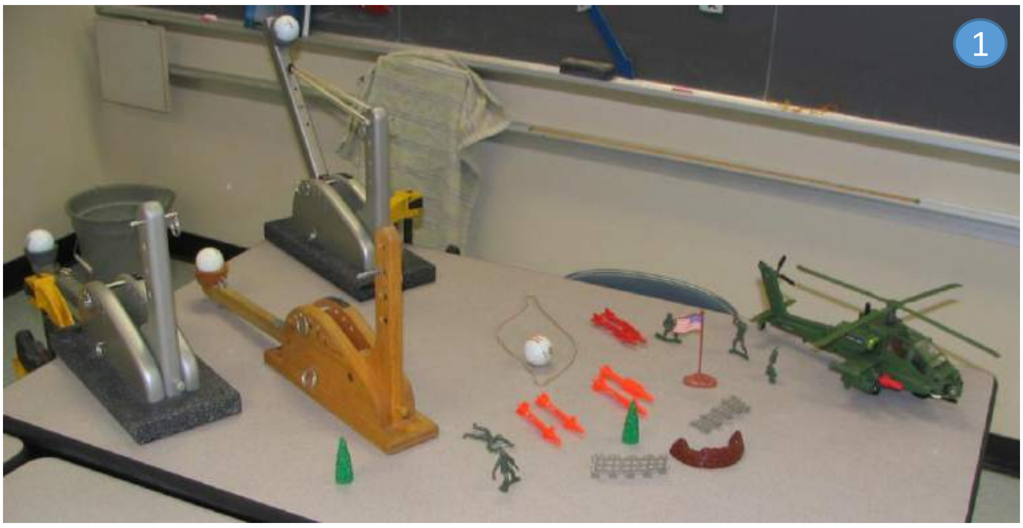
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Assorted Military Vehicles and Toy Soldiers	1	$20-40	The essential pieces are tanks, cannons, and a helicopter.

APPLICATION

Before Class: Layout the "attack".

In Class: This training aid is meant to fill the classroom to develop the spatial aspect of the problem. The cannons (artillery) are positioned at one corner, 1 the helicopter is hung from the ceiling in the middle, 2 and the tanks are on a moving cart on the other side of the classroom. 3 Of note, the cannons pictured are catapults we utilize during the kinetics block of the course. The situation is developed that the scout helicopter (translating and rotating) uses a laser designator and "sees" the approaching tanks moving at a relative velocity at an instant in time. The question to be answered is to determine the absolute velocity of the approaching tank column (relative to the stationary artillery unit) and then to determine how many minutes are left before the advancing tanks are within range of the artillery.



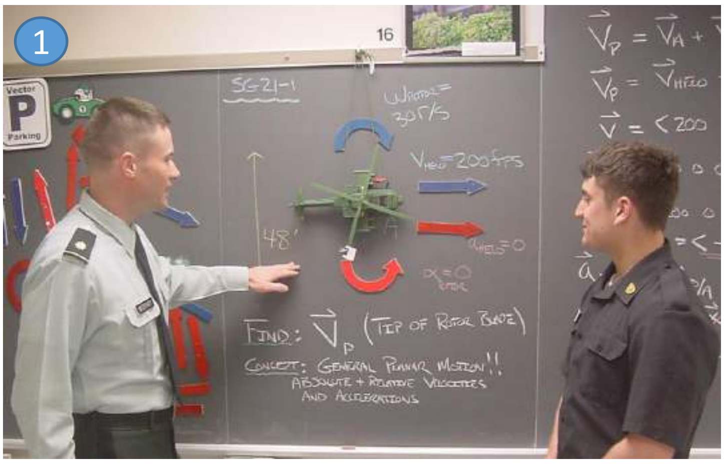
THE HELICOPTER

DYNAMICS

Keywords: General Planar Motion, Non-Rotational, Rigid, Rotational, Translational

Submitted by: Tom Messervey

Model Description: This training aid demonstrates the translational and rotational kinematics of a rigid body in a non-rotational frame. This demonstration should take 10-15 minutes. 1



Engineering Principle: Building upon the concept of Rotation About a Fixed Axis (RAFA), the helicopter provides an excellent example to step into general planar motion (GPM) by first demonstrating the hovering helicopter (RAFA) and then demonstrating the helicopter flying (GPM). Intuitively, this is comfortable and the development of vector equations becomes the tool to describe what the students already know. 2

$$v_b = v_a + v_{b/a} \qquad a_b = a_a + a_{b/a}$$

$$v_b = v_a + \omega \times r_{b/a} \qquad a_b = a_a + \alpha \times r_{b/a} - \omega^2 r_{b/a}$$

$$\alpha = Angular\ Acceleration \qquad \omega = Angular\ Velocity$$

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Toy Helicopter	1	$5-25 depending on size	A bigger model is useful here to better see the discussed principles in action.

APPLICATION

Before Class: Acquire a toy helicopter.

In Class: Helicopter clips start the lesson and the helicopter training aid is utilized to motivate the need for the derivation of the equations. The example problem for the lesson is then solved.

Additional Application: Helicopter Trivia - American and British helicopter rotors rotate counter clockwise. Soviet and French rotors rotate clockwise.
As a helicopter travels forward, the velocity of the rotor blades on each side of the aircraft becomes unequal. This produces an uneven amount of lift and would cause the aircraft to tilt to one side if left uncorrected. Modern helicopters address this dissymmetry of lift by allowing the blades to flap up on the advancing side and down on the retreating side and hunt forward on the advancing side and lag on the retreating side.

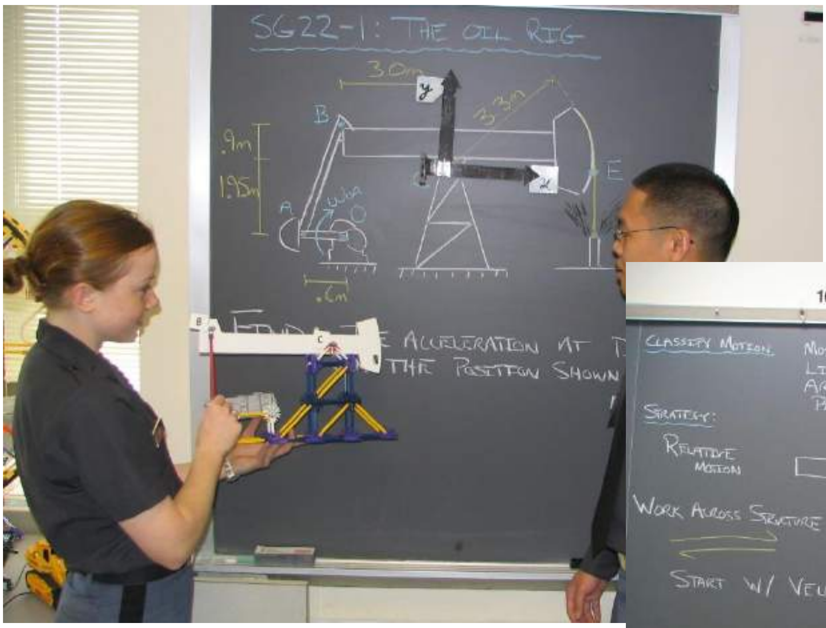
THE OIL RIG

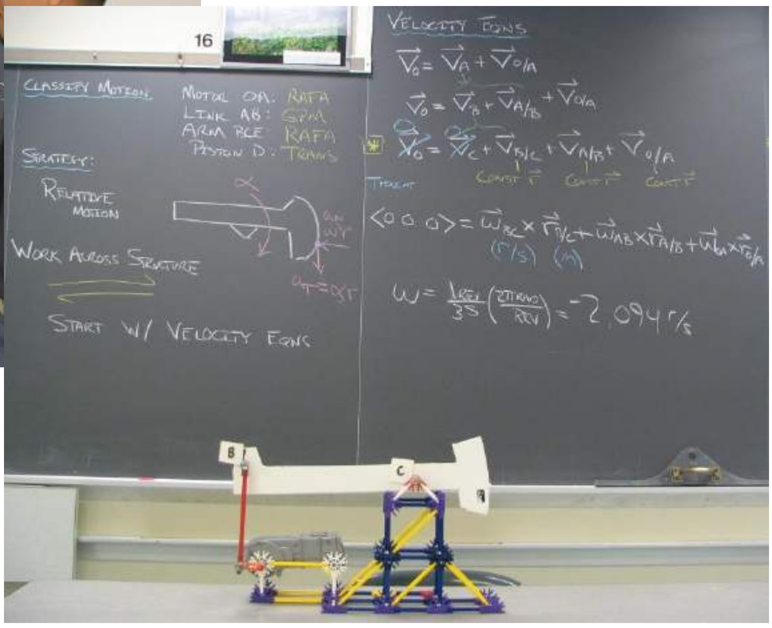
DYNAMICS

Keywords: General Planar Motion, Rotation, Translation

Submitted by: Tom Messervey

<u>Model Description</u>: This training aid demonstrates the kinematics of multiple connected rigid bodies in translation, rotation, or general planar motion. This demonstration should take 10-15 minutes.





<u>Engineering Principle</u>: This training aid demonstrates the kinematics of a multi-body structure. Motion for each part of the structure is classified and discussed. A KNEX motor brings the training aid to life. With the oil rig in motion, students readily classify the motion of each part of the structure. A discussion of point and body properties and their interaction across the structure becomes a natural extension of member classification. Given the angular velocity of the motor, vector equations are then utilized to find the acceleration of the oil piston.

$$v_b = v_a + v_{b/a} \qquad\qquad a_b = a_a + a_{b/a}$$

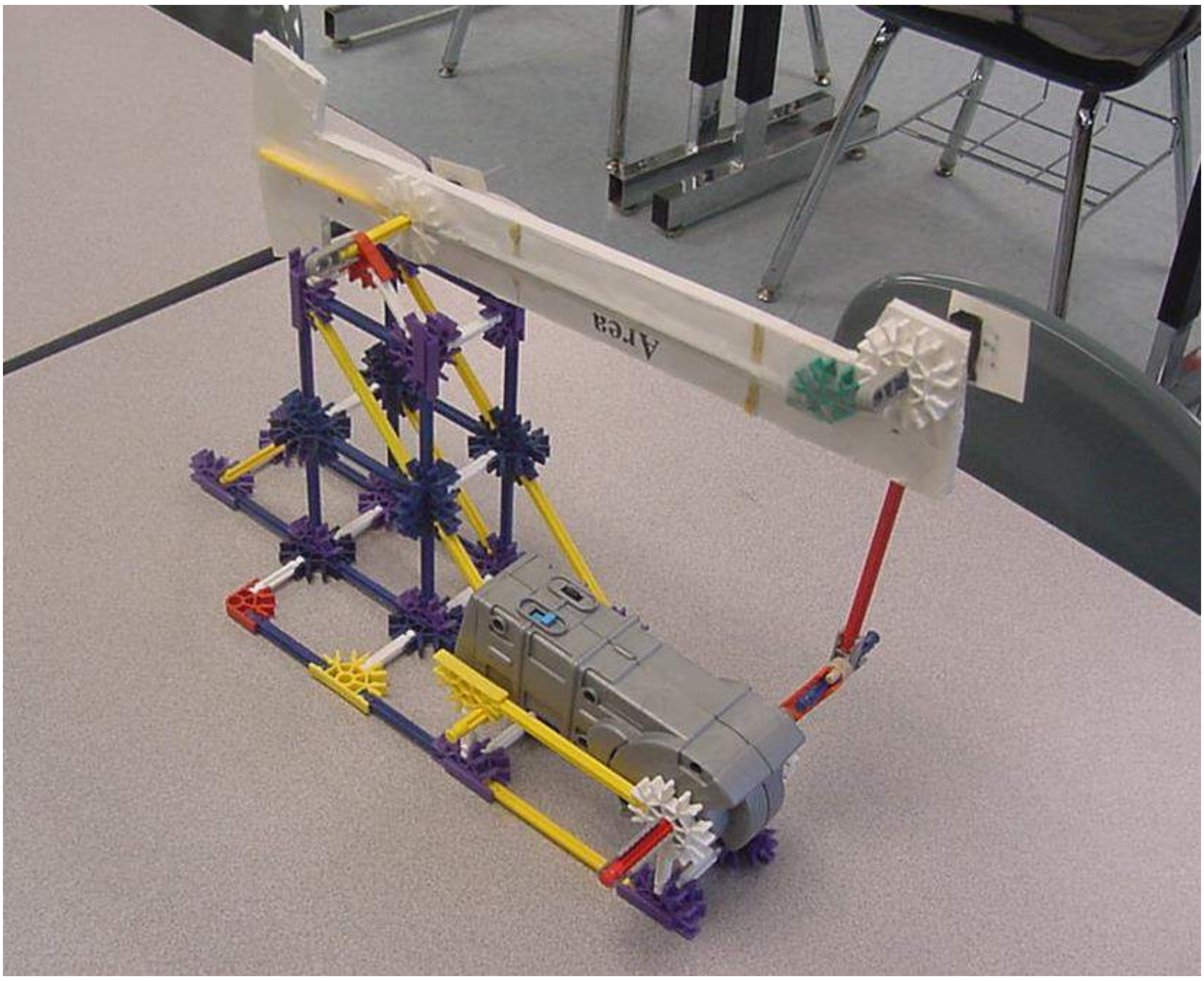
REQUIRED ITEMS

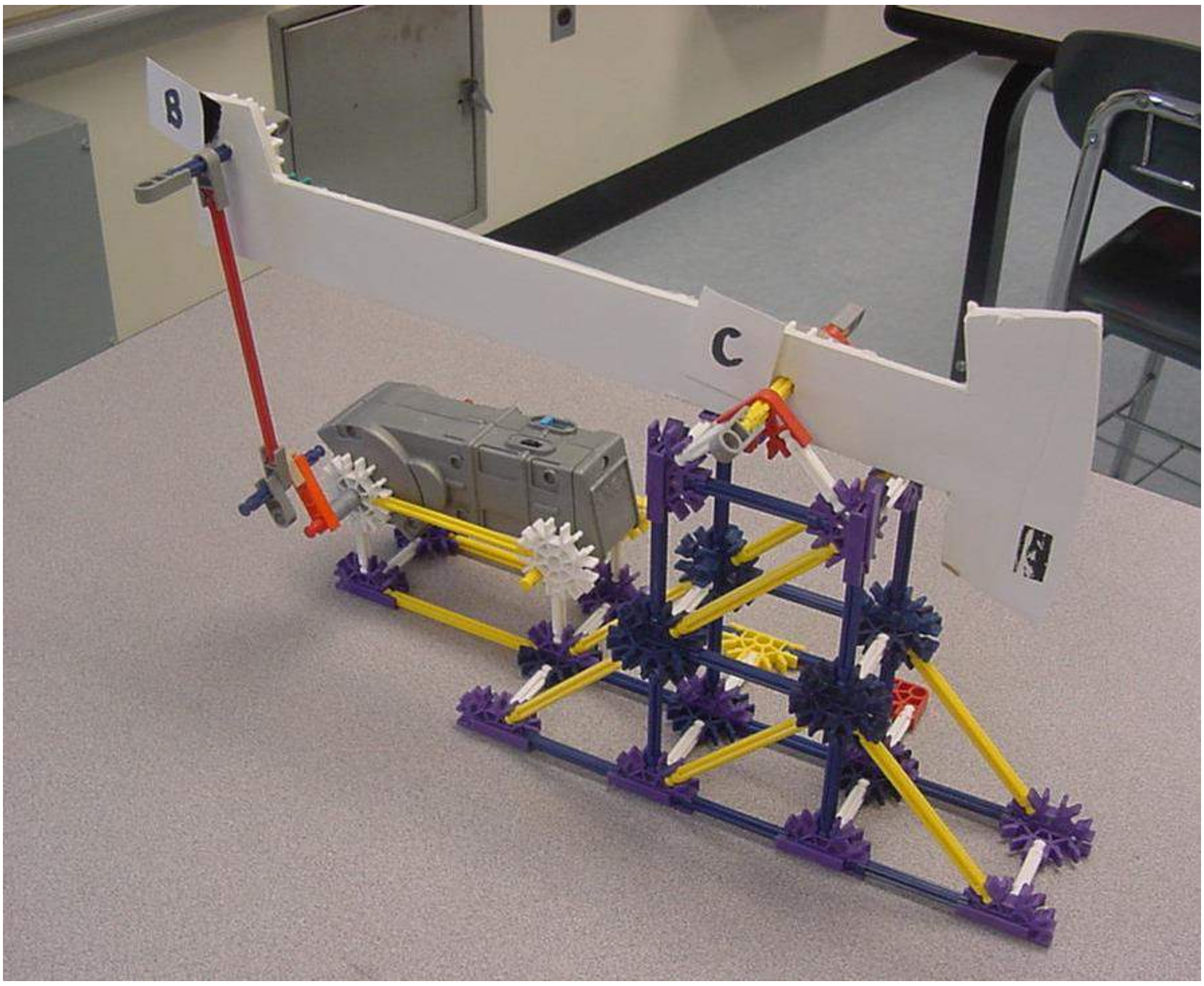
Item	Qty	Cost and Build Time	Description/Details
Oil Rig	1	$30; 45 minutes	Made of KNEX, a truss holds the main arm and a box frame holds the motor. The rig is scalable.
Foam Board	1	$5; 15 minutes	This is used to make the main arm.
KNEX Motor	1	$20	This provides the rotation.

APPLICATION

Before Class: Prepare the beam with the lines drawn on it.

In Class: Typically, the training aid is hidden until the problem is developed and motion is classified. The motor turns in both directions and at multiple speeds which allows the opportunity to get the direction "wrong" (in comparison with the figure on the board) at first and the fast setting is quite humorous to watch.





Additional Application: Trivia - Did you know? Oil rigs don't "suck" oil out of the ground but develop pressure into the ground which "pushes" the oil out.

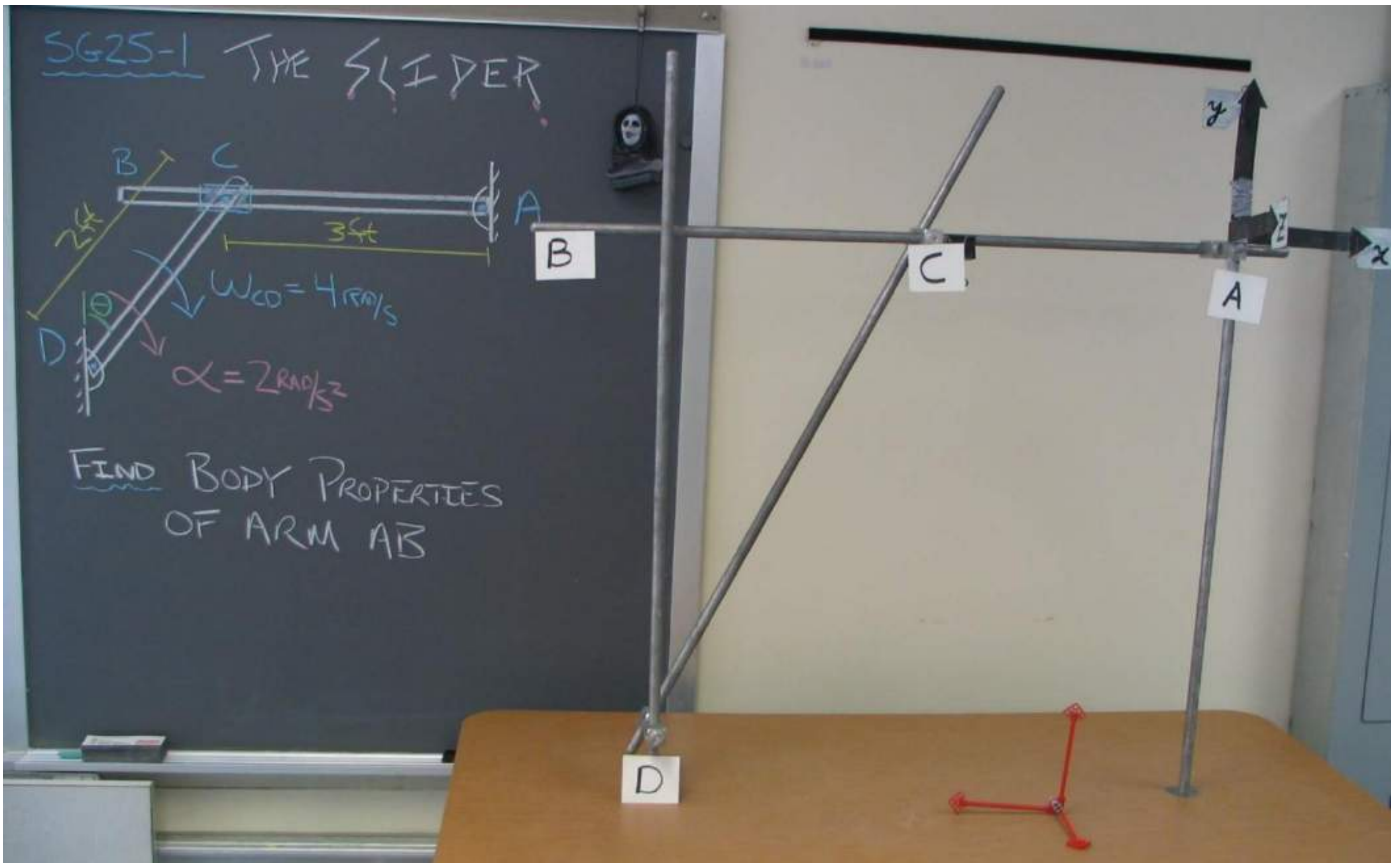
THE SLIDER

DYNAMICS

Keywords: Angular Acceleration, General Planar Motion, Rotational, Translational

Submitted by: Tom Messervey

Model Description: This training aid demonstrates the translational and rotational kinematics of rigid bodies in translating as well as translating and rotating reference frames. This demonstration should take 15 minutes.



Engineering Principle: This lesson reinforces the vector equations for relative motion shown below:

$$v_b = v_a + v_{b/a}$$

$$v_b = v_a + \Omega \times r_{b/a} + (v_{v/a})_{\mathrm{xyz}}$$

$$a_b = a_a + a_{b/a}$$

$$a_b = a_a + \dot{\Omega} \times r_{b/a} + \Omega \times (\Omega \times r_{b/a}) + 2\Omega \times (v_{b/a})_{\mathrm{xyz}} + (a_{b/a})_{\mathrm{xyz}}$$

REQUIRED ITEMS

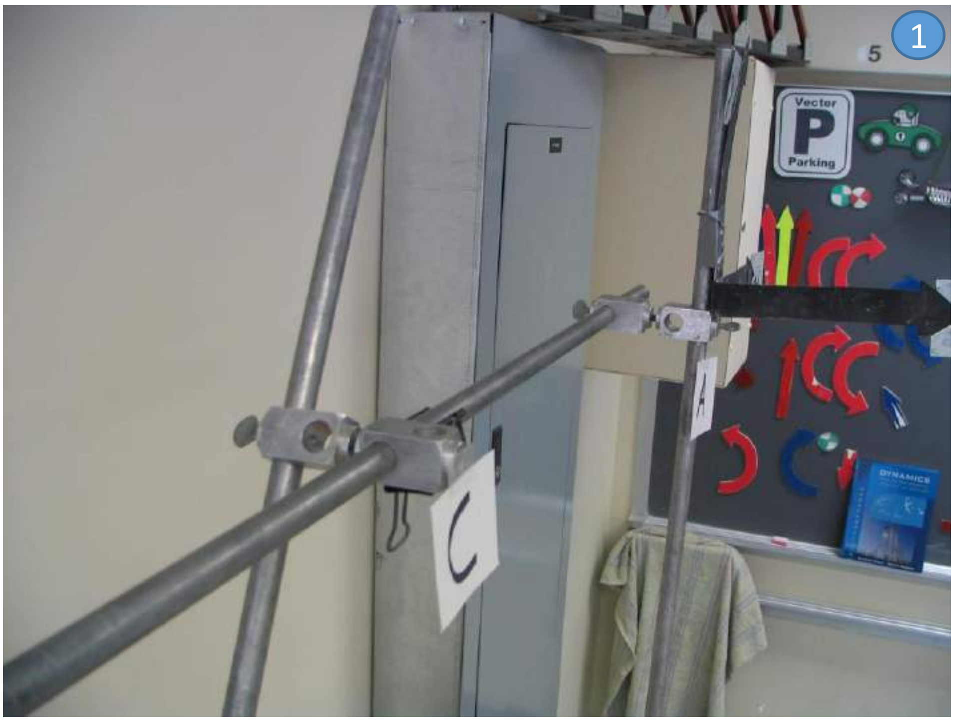
Item	Qty	Cost and Build Time	Description/Details
Metal Rods	4	$40; 45-60 minutes	These mount directly into the desk top pictured
Hinge Connectors	6	$30	Used for many different configurations of these rods for various example problems (pictured)

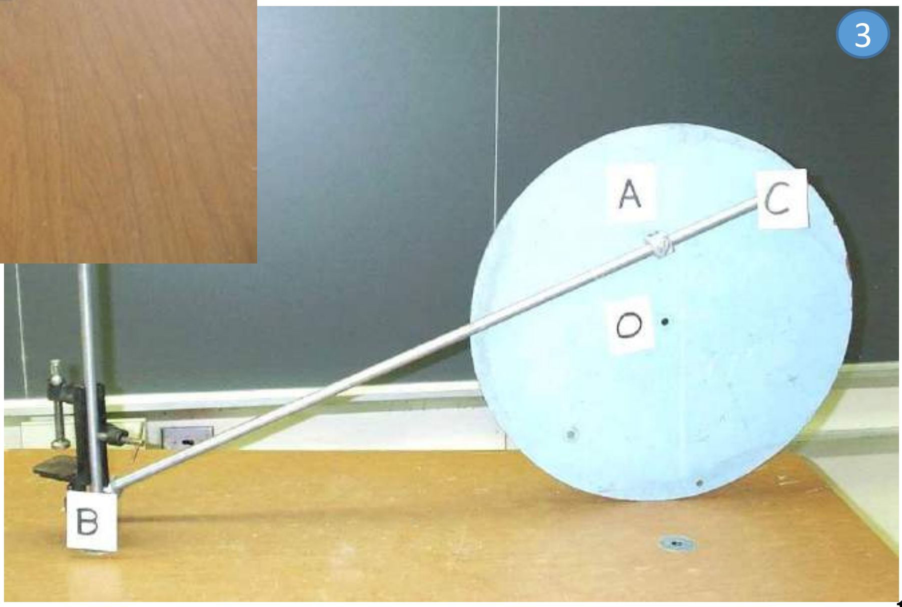
APPLICATION

Before Class: Build the slider.

In Class: The model demonstrates the example problem for the lesson. The angular velocity and angular acceleration of bar DC are provided, and the angular velocity and angular acceleration of bar BCA is desired at the instant in time bar BCA is horizontal. The collar at C is free to slide back and forth. As pictured, an "alligator" clip is holding the collar in place.

The hinge connectors pictured below ("pillow box" connectors) are usually used to secure one rod to another. 1 However, by attaching two of them together with a small screw segment 2, they are free to rotate about each other and maintain a grip on whatever they are holding. This same idea is used in a separate slider problem where a disk is attached to a bar by a collar that is free to rotate and which allow the bar to slide through it. 3 Cenco right angle clamp holders also can be made to work. 4





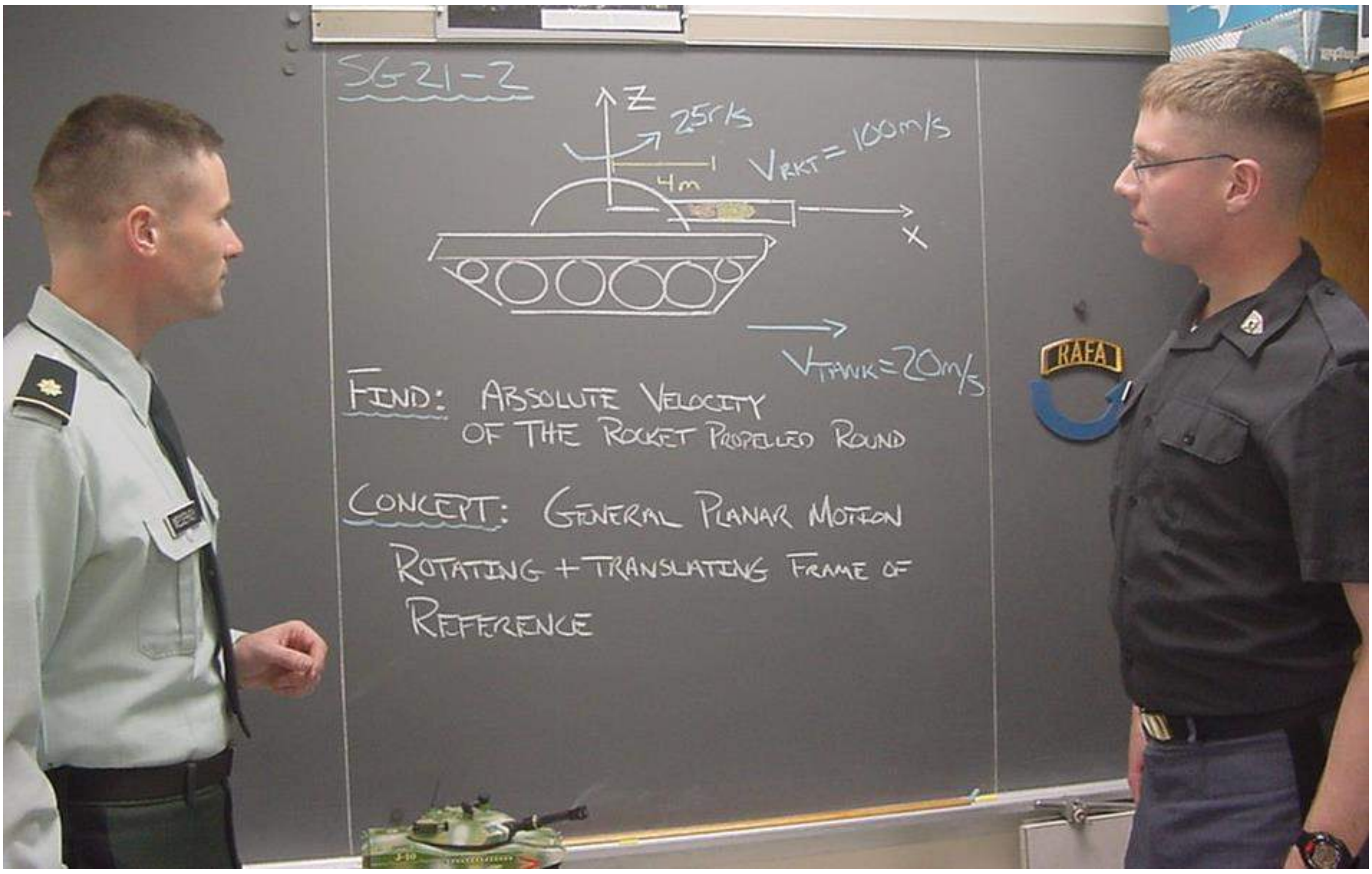
THE TANK

DYNAMICS

Keywords: General Planar Motion, Rotational, Translational

Submitted by: Tom Messervey

Model Description: This training aid demonstrates the translational and rotational kinematics of a rigid body in a translating and rotational frame. This demonstration should take 30 minutes.



Engineering Principle: Building upon general planar motion (GPM) in a non-rotational frame, this model develops the need to address GPM in a rotational frame by examining a projectile exiting a rotating gun tube of a moving tank. The fact that the projectile has its own velocity and that its distance from the tank changes with time motivates the fact that something is happening differently both physically and mathematically from the non-rotational previously discussed and leads to the derivation of the following vector equations:

$$v_b = v_a + v_{b/a}$$

$$v_b = v_a + \Omega \times r_{b/a} + (v_{v/a})_{\text{xyz}}$$

$$a_b = a_a + a_{b/a}$$

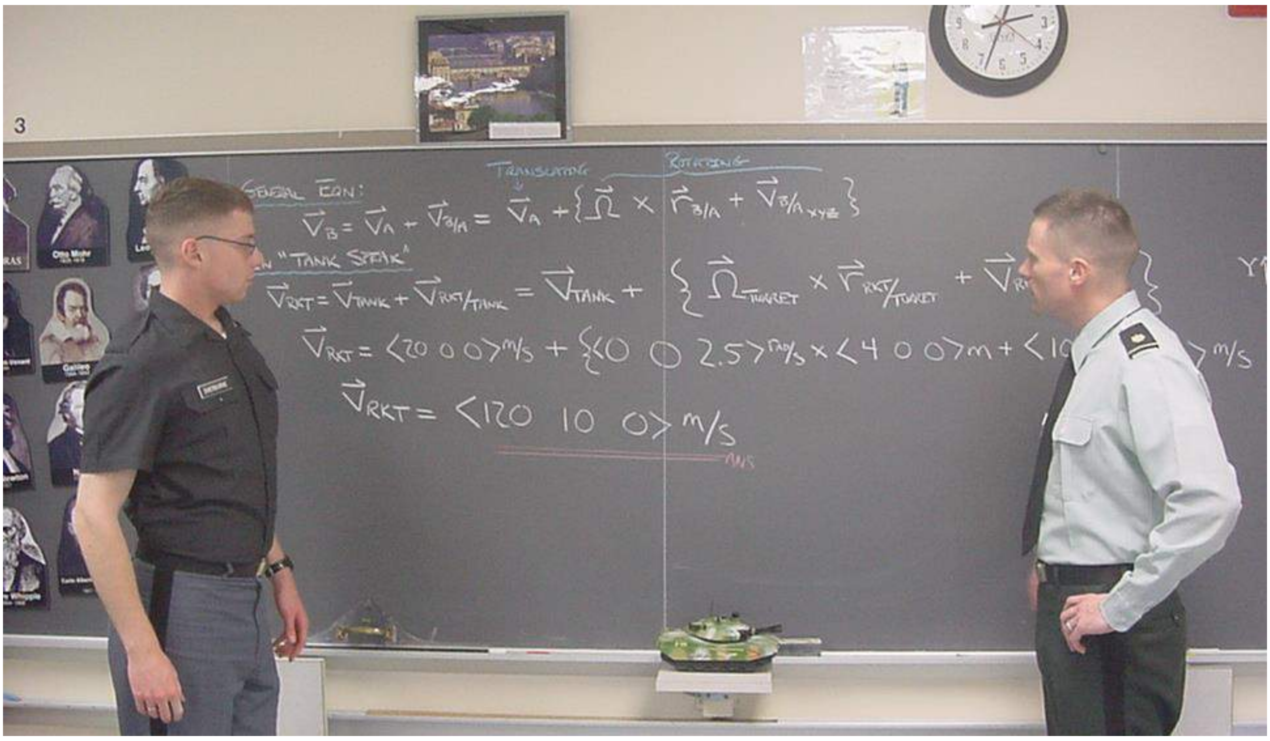
$$a_b = a_a + \dot{\Omega} \times r_{b/a} + \Omega \times (\Omega \times r_{b/a}) + 2\Omega \times (v_{b/a})_{\text{xyz}} + (a_{b/a})_{\text{xyz}}$$

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Toy Tank	1	$5-20	Ensure the turret swivels.

APPLICATION

In Class: Tank clips start the lesson and the tank training aid is utilized to motivate the need for the derivation of the equations. The example problem for the lesson is then solved examining the absolute velocity and acceleration of the projectile before it leaves the tube.



Additional Application: Tank Trivia - Did you know? Tanks have multiple targeting sensors which include a wind sensor on the back of the tank and a gyroscope which measures the angle of inclination or declination the tank is sitting or moving upon. When a gunner lazes a target, the computer measures the relative motion between the tank and its target, uses the wind and gyro, and instantaneously executes the targeting solution that will ensure steel target. The M1A2 Abrams also now includes independent targeting systems. This allows a Tank Commander (TC) to identify a target separate from the gunner such that when the gunner finishes a firing mission, a simple button automatically adjusts the turret to the secondary target.

PROJECTILE MOTION

DYNAMICS

Keywords: Acceleration, Projectile Motion, Velocity

Submitted by: Charles Packard

Model Description: This is a simple demonstration of the basic principles and behavior underlying projectile motion. A nerf gun is used to show that projectile motion can be modeled by a particle having a vertical component of motion with constant acceleration, and a horizontal component with constant velocity (zero acceleration). This demonstration should take 5-8 minutes.

Engineering Principle: A projectile follows a curved path that is approximately parabolic, provided that air resistance can be neglected. This curvilinear motion is planar (approximating a portion of an inverted parabola in a vertical plane), and describable in terms of horizontal (*x*) and vertical (*y*) coordinates. The motion of the projectile can be modeled by a particle having a vertical component with constant acceleration (*g*, downward) and a horizontal component with constant velocity (zero acceleration). The following equations describe the particle's motion in terms of these coordinates:

Horizontal Coordinate: $x = x_o + (v_x)_o t$

Vertical Coordinate: $y = y_o + (v_y)_o t - \frac{gt^2}{2}$

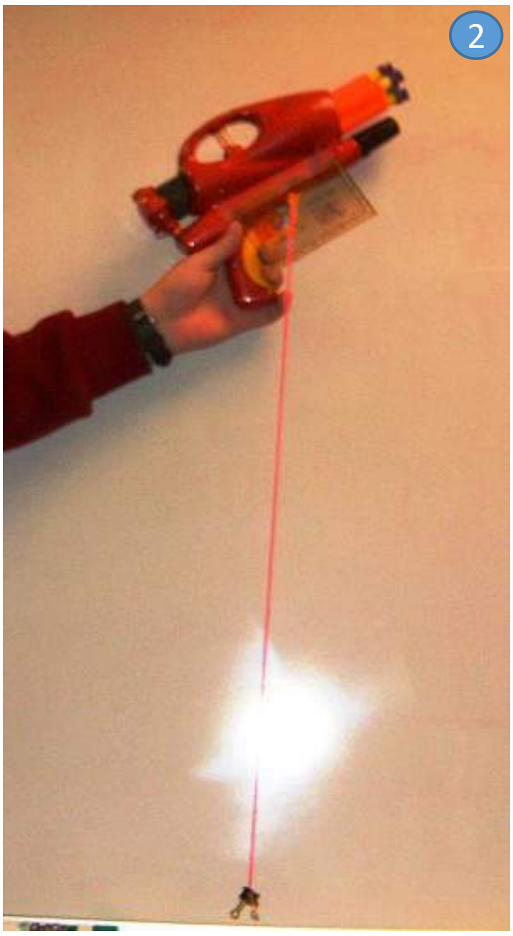
Notice that the two equations are independent—the horizontal and the vertical components of the particle's motion can be considered separately. If air resistance were not negligible, however, such as for a paper wad, the equations would be coupled—and more complicated.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Nerf Gun 1	1	\$10-15	Any model works as long as it contains soft, nerf-like projectiles, to which a linear impulse is applied by a compressed spring.
Protractor	1	\$4	The protractor is used to measure the angle of the toy gun's inclination when the soft projectile is fired.
Yard Stick	1	\$5	You can make a plum bob out of a string and a small weight like a nut. It is used in conjunction with the protractor to determine the gun's angle with respect to the horizontal plane.
Tape Measure	1	\$5	The tape measure is used to measure the horizontal distance from the launch point to the impact point.
Stop Watch	1	\$5	The stopwatch is used to measure the projectile time-of-flight.

APPLICATION

<u>Before Class</u>: Mount the protractor to the toy gun so that the flat edge is aligned with the barrel and the curved edge faces down. Attach the "plumb bob" to the middle of the protractor's flat edge, to permit angular measurements of the barrel's inclination angle. Make these attachments in such a way that the operation of the toy is not hampered. 2 Experiment with the toy gun so that you have a feel for how far and how high the soft projectile will go within the classroom.



<u>In Class</u>: Introduce the equations above and use the toy gun to validate them. Use students as time keeper, recorder, impact point marker, etc.

Ask students to predict which will hit the ground first, a soft projectile fired by the toy gun, or a projectile dropped from the firing height at the same time. Demonstrate that regardless of the firing height, both projectiles impact the ground at the same time as long as the barrel is horizontal. This shows that the vertical and horizontal components are independent.

Determine horizontal and vertical launch velocities from measurements of angle of inclination, launch height, and time of flight using the equations above.

Demonstrate, space permitting, that different angles of fire can result in the same range. (This may be difficult if your class has a low ceiling.)

Observations: The students should observe that a projectile dropped from some height *h* impacts the ground at the same time as one that is fired horizontally by a toy gun from the same height. The students should also observe that there are generally two angles of fire which result in the same impact point—the only exception is the 45^o firing angle, which only has one.

<u>Additional Application</u>: Once the firing velocity is determined, the students can determine the firing angle and height required to hit some target of interest, say the mascot of the school's arch rival on the sport field!

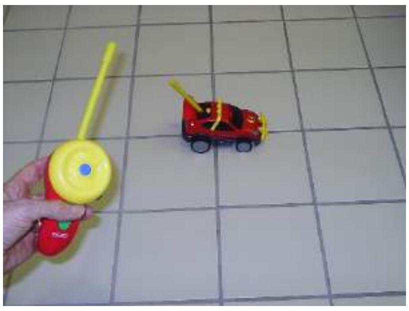
RECTILINEAR MOTION

DYNAMICS

Keywords: Coordinate, Displacement, Position, Total Distance Traveled

Submitted by: David Hampton

Model Description: This is a simple demonstration to distinguish among a particle's coordinates, position, displacement, and total distance traveled. A remote-controlled car is used to demonstrate the distinctions, for a particle in rectilinear motion. This demonstration should take 5-8 minutes.



Engineering Principle: The *position* (location) of a particle in rectilinear motion can be described by Cartesian *coordinates*. If the positive x-axis of a Cartesian (x-y-z) coordinate system is lined up with a particle's direction of travel, the single coordinate x will suffice to locate the particle's position. In scalar form, the particle is said to be located at position x, or, more completely, at (x,0,0). Coordinates can have positive or negative values. In vector form, the particle is located at $x\boldsymbol{i} + 0\boldsymbol{j} + 0\boldsymbol{k}$, or simply $x\boldsymbol{i}$. Any of these four expressions suffices to locate the particle; but the particle's position should always be considered as a vector quantity, since it represents both a *magnitude* (distance) and a *direction* from the origin. The coordinates are the scalar quantities, which—with the coordinate system—describe the particle's location. If the coordinate system is rotated clockwise through some angle θ (say, 35°), then two coordinates will now be necessary to describe the particle's position: (x,y), (x,y,0), $x\boldsymbol{i} + y\boldsymbol{j}$, or $x\boldsymbol{i} + y\boldsymbol{j} + 0\boldsymbol{k}$. Again, the position is normally described relative to the coordinate system origin, and is a vector quantity.

The *displacement* of a particle describes its position relative to another (typically fixed) reference point, not necessarily the origin of the coordinate system. If the reference position is , the displacement at any point $x\boldsymbol{i}$ is the vector $(x - x_1)\boldsymbol{i}$, or simply $x - x_1$, with the unit vector understood (for rectilinear motion in the x direction). The *position* of the particle is simply its *displacement* from the origin.

The total distance traveled differs from the displacement in two significant ways:

1) The total distance traveled is a positive scalar; but the displacement is a vector, even if given in scalar form with the unit vector understood.

2) The total distance traveled from position 1 to position 2 represents the length of the actual path (taking into account any overlaps) traversed by the particle along the path it traveled; the displacement, on the other hand, simply represents the vector (even if given in scalar form as *x*) from position 1 to position 2, and gives no information about the path traveled. For example, the particle could have started and stopped at the same location, after traveling a significant distance. (In rectilinear motion, of course, this would entail the particle's reversing direction at least once.) In this case the displacement would be a vector of magnitude zero; and the total distance traveled, some nonzero scalar.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Model Car 1	1	$5-30	Any small model will suffice (even a book or an eraser will do), but a rolling vehicle is preferred—and if it is remotely controllable it will be more memorable for the students.

APPLICATION

<u>Before Class</u>: Mark a coordinate system (with origin) on the floor (or desk) and practice the demonstration. Be sure to have the room arranged so that students can see the demonstration.

<u>In Class</u>: Move (or operate, if remotely controllable) the vehicle from the origin along the *x* axis (1) in a positive direction, (2) in a negative direction, and (3) along a path that includes motion in both positive and negative directions. Discuss how to locate the vehicle using the coordinate system. Discuss also the advantage of a coordinate system that has an axis aligned with the car's motion, for rectilinear motion. Use marks or tiles on the floor to quantify coordinates, position, and displacement; note the coordinate signs and sign changes. Determine the total distance traveled for each of the three motions, noting that the total distance traveled is always nonnegative.

Observations: The students should observe that coordinates can be zero, positive, or negative; but that the total distance traveled is always nonnegative. They should note that for rectilinear motion whenever the vehicle reverses direction it passes through a condition of zero velocity. The times or locations of zero velocity may be needed for determining total distance traveled. Students should observe that, for motion only in the positive *x* direction, the total distance traveled and the *x* coordinate have the same value; but that for motion only in the negative *x* direction the total distance traveled and the coordinate do *not* have the same value. In particular, the former is the absolute value (magnitude) of the latter.

<u>Additional Application</u>: Rotate the coordinate system through some angle (between 30° and 60° , for visual clarity), and repeat the demonstration. (Alternatively, but less desirably, you could use the same coordinate system and rotate the "roadway.") Note the increase in complexity of the mathematical description for the vehicle motion—even though the vehicle still has the same rectilinear motion—since now two coordinates are required instead of one. Remark on the desirability of choosing your coordinate system to simplify the mathematical description, where possible.

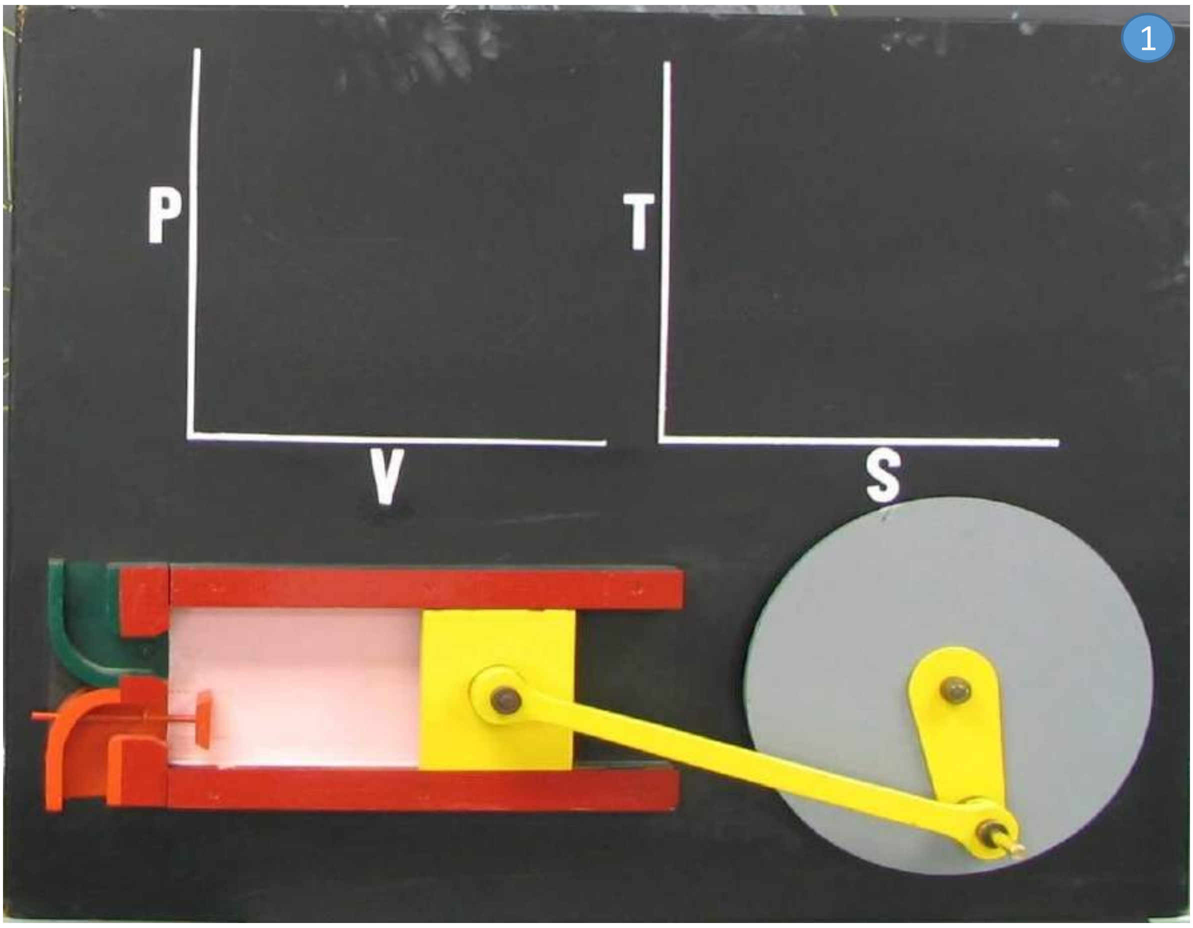
CHOO CHOO TRAIN

DYNAMICS

Keywords: Acceleration, Engine Cycle, Relative Motion, Velocity

Submitted by: Thomas Messervey

Model Description: Relative motion and no-slip wheel relationships are brought to life by means of a moving locomotive train. 1 This demonstration should take 10 minutes.



Engineering Principle: The following relationships are utilized to investigate the velocity and acceleration of the engine piston and push arm given a train velocity and instantaneous position of the wheel.

No Slip Wheel:

$$v_{PC} = 0 \qquad v_{ctr} = \omega_{wh} r_{wh}$$

$$a_{PC} = \omega_{wh}^{2} r_{wh} \qquad a_{ctr} = \alpha_{wh} r_{wh}$$

Relative Motion:

$$v_b = v_a + v_{b/a}$$

$$a_b = a_a + a_{b/a}$$

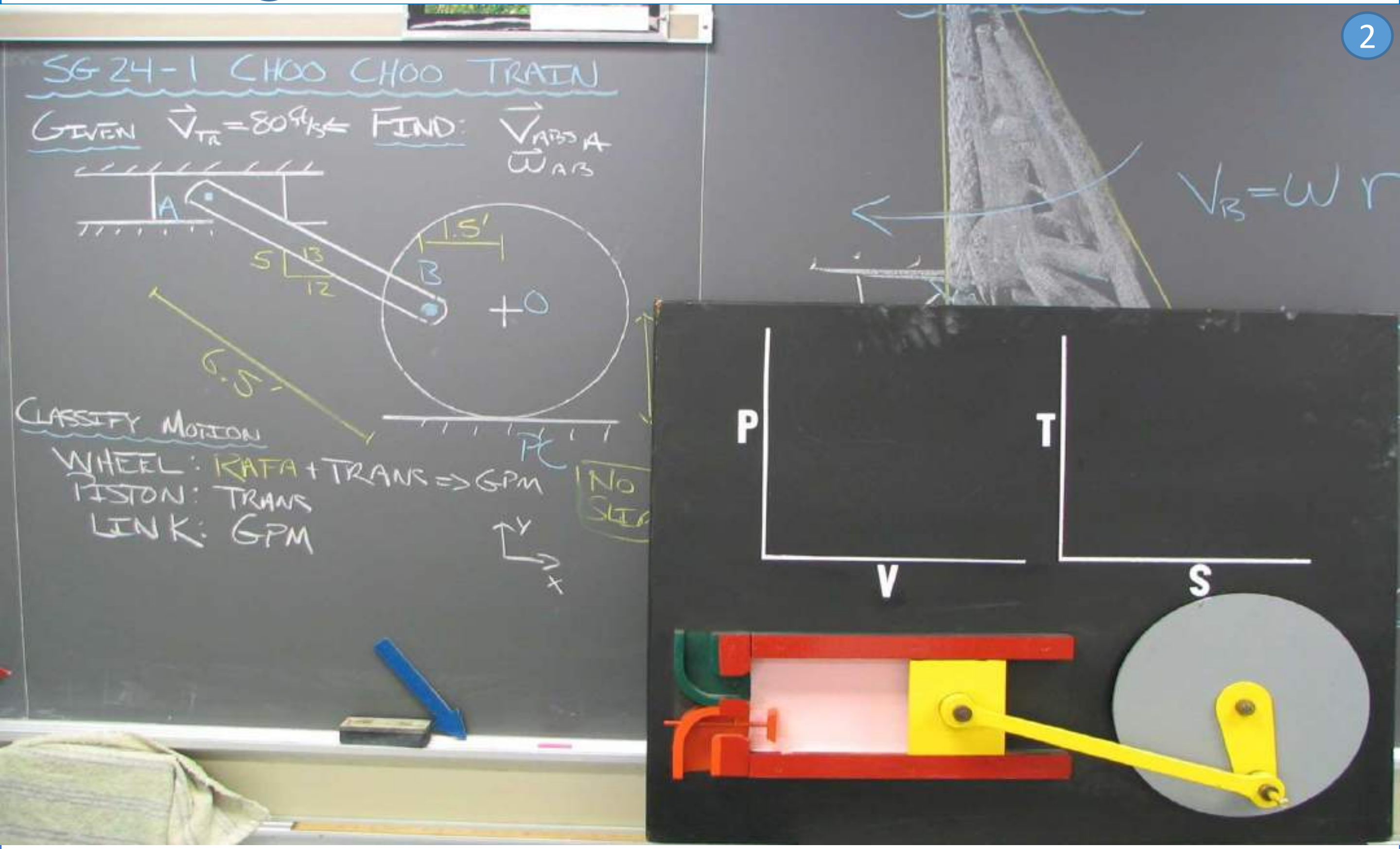
REQUIRED ITEMS

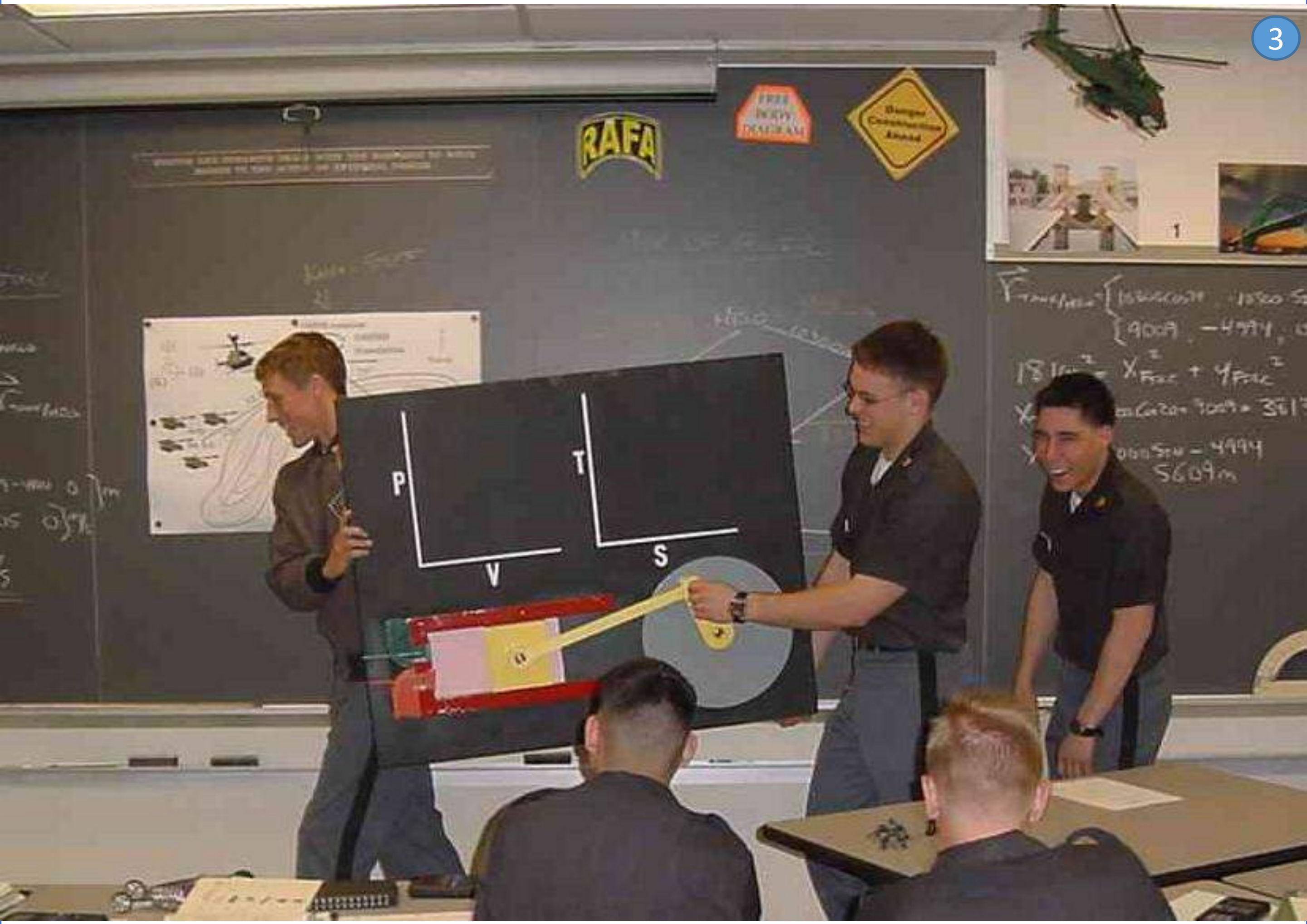
Item	Qty	Cost and Build Time	Description/Details
Demo Board	1	$50 in materials; 2 hours	Rotating wheel, arm, and sliding piston that represent an engine cycle. The demo board can be made of ½ inch plywood. Base dimensions are approximately 4 feet long by 3 feet high. Further dimensions can be seen in Image 2. This is a difficult and time consuming build.

APPLICATION

Before Class: Build the demonstration board.

In Class: Read the problem and ensure setup is complete. 2 The board is utilized to assist in classifying the motion for the wheel, push arm, and piston. Because the board isn't translating like the train, it brings up the fun moment of having students reenact a live "Choo Choo train" across the classroom (good laugh for all). 3





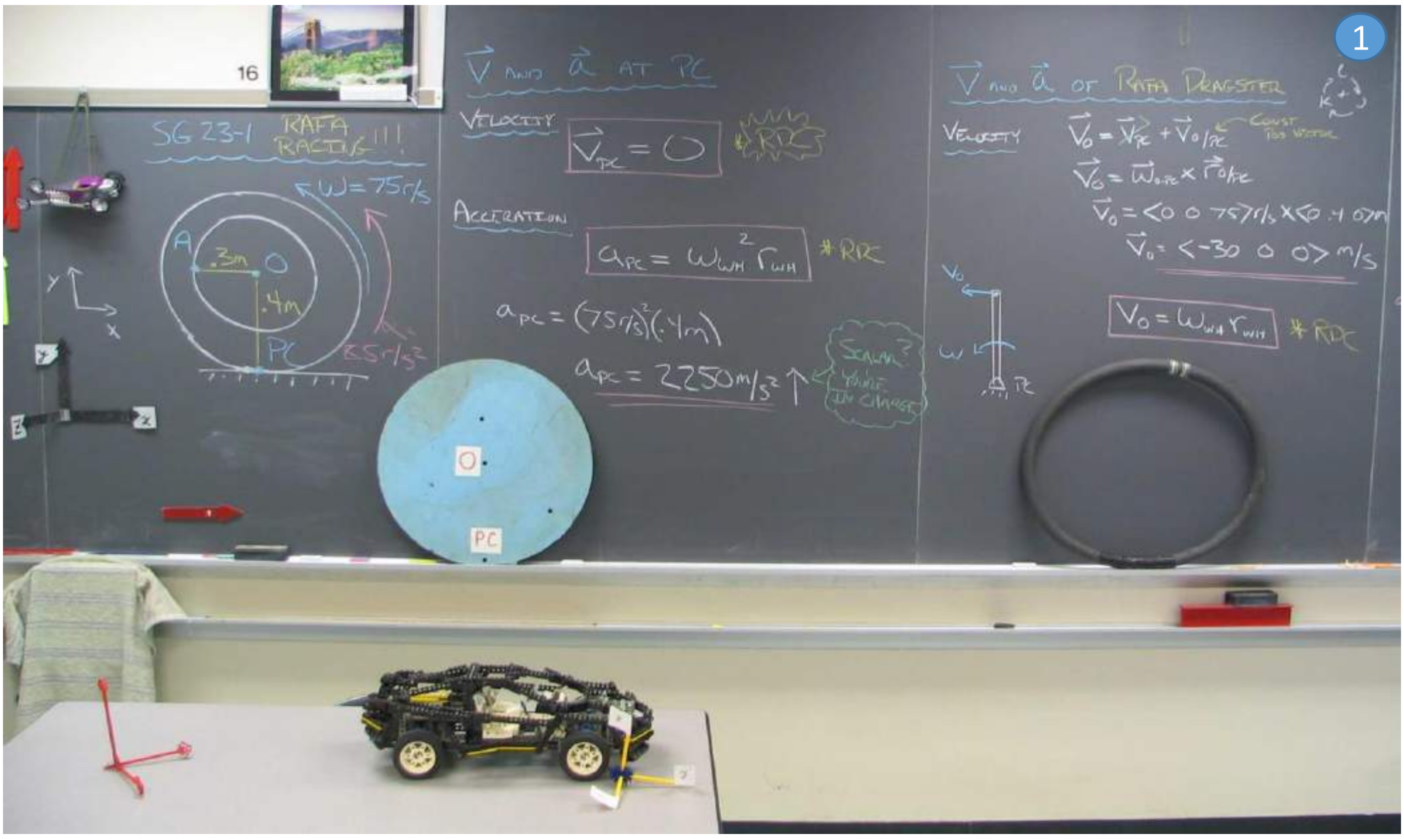
NO SLIP WHEEL

DYNAMICS

Keywords: Instantaneous Center of Zero Velocity (ICZV), No-slip, Rolling

Submitted by: Tom Messervey

Model Description: A disk, remote control bulldozer, and foam inner tube are utilized to demonstrate no-slip wheel relationships. (1) This demonstration should take 8-10 minutes.



Engineering Principle: Applicable equations

$v_{PC} = 0$ $\qquad$ $\alpha = Angular\ Acceleration$

$a_{PC} = \omega_{wh}{}^2 r_{wh}$ $\qquad$ $\omega = Angular\ Velocity$

$v_{ctr} = \omega_{wh} r_{wh}$ $\qquad$ $wh = Wheel$

$a_{ctr} = \alpha_{wh} r_{wh}$ $\qquad$ $PC = Point\ of\ Contact$

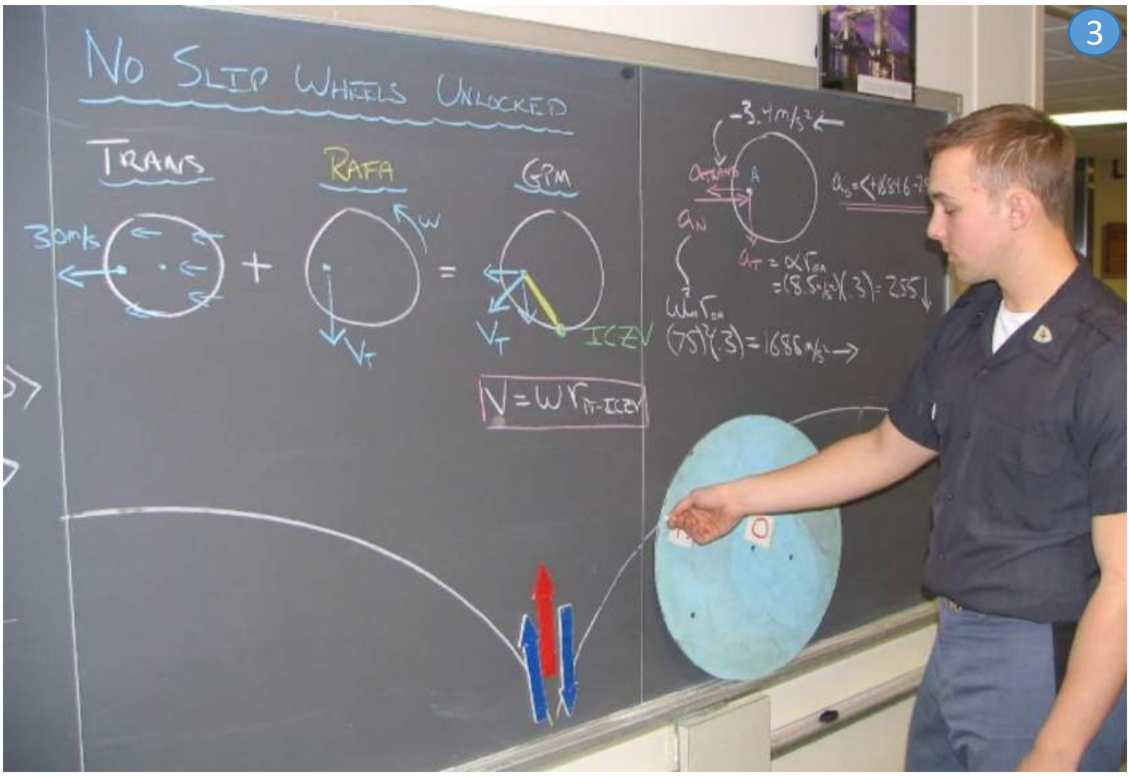
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Toy Bulldozer	1	$15	Used for track and motion
Disk With Holes	1	$10; 20 minutes	Used to trace position of any point while rolling
Foam Inner Tube	1	$10; 10 minutes	Used to show no velocity at the point of contact

APPLICATION

Before Class: Prepare foam inner tube and disk with holes in it.

In Class: Discovering that the velocity at the point of contact for a no-slip wheel always gets a reaction from students. First it is plainly stated. Asking for "non-believers", a volunteer places his or her finger on a point on the bottom of the track of a remote control bulldozer. As the bulldozer moves forward, the student's finger doesn't move! For those who can't see, the larger foam inner tube really makes this clear to see. 2 Stating that this seems like some sort of magic trick, one offers a mathematical demonstration with the disk. Tracing the position of the point of contact on a chalkboard as the disk rolls forward, one can than show that the velocity must change direction as the point of contact touches the contact surface. 3 In order for this to occur, it must pass through zero. Additionally, to change the velocity, acceleration must be present. The disk can also be utilized to define and demonstrate the instantaneous center of zero velocity (ICZV) at the PC. Rocking the disk back and forth, it is clearly shown that the entire wheel rotates about the ICZV at any given instant.



A DAY AT THE RACES

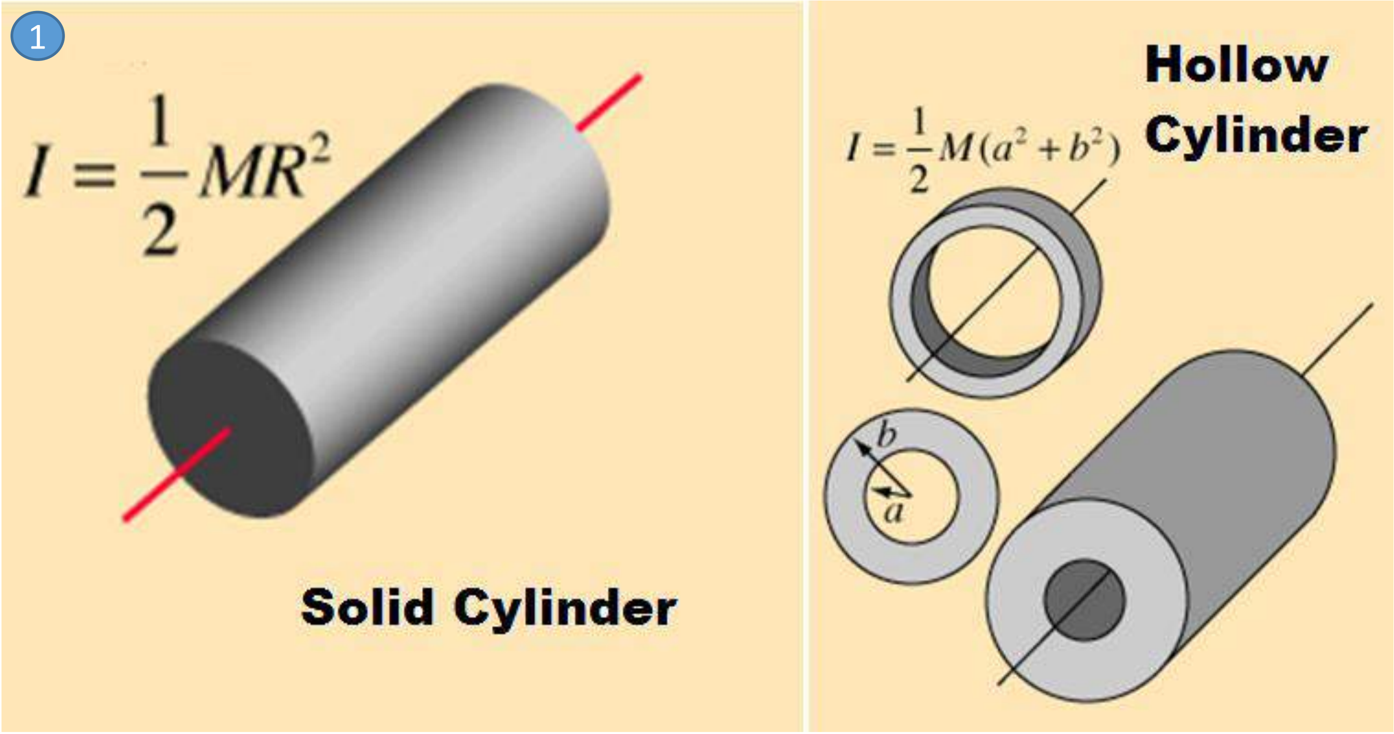
DYNAMICS

Keywords: Axis of Rotation, Cylinder, Mass, Moment of Inertia, Rotating Body, Translation

Submitted by: Allen Estes, Charles Packard, Tom Messervey

Model Description: This is a demonstration of the basic principles underlying the behavior of rotating bodies. A cylinder "race" is used to show that the closer the mass of an object is concentrated to an axis of rotation, the faster it will spin because it has a lower *moment of inertia*, which is a measure of a body's resistance to rotation. This demonstration should take 15-20 minutes.

1



Engineering Principle: The *mass moment of inertia* is a rigid body's resistance to rotation and is a measure of the distribution of mass of a rigid body relative to a given axis of rotation. In its most general form, the *mass moment of inertia* is given by:

$$I = \int_B r^2 dm$$

where:
"I" is the mass moment of inertia
"dm" is a differential element of mass of the rigid body
"r" is the perpendicular distance from the axis of rotation to a differential element of mass
"B" represents the rigid body

For a solid cylinder and a hollow cylinder, the equations for the *mass moment of inertia* about the axis of interest in the demonstration are reduced (http://hyperphysics.phy-astr.gsu.edu/hbase/mi.html#mi). 1 "M" represents the mass of the rigid body and "R" represents the radius of the solid cylinder, and "a" and "b" represent the inner and outer radii of the hollow cylinder.

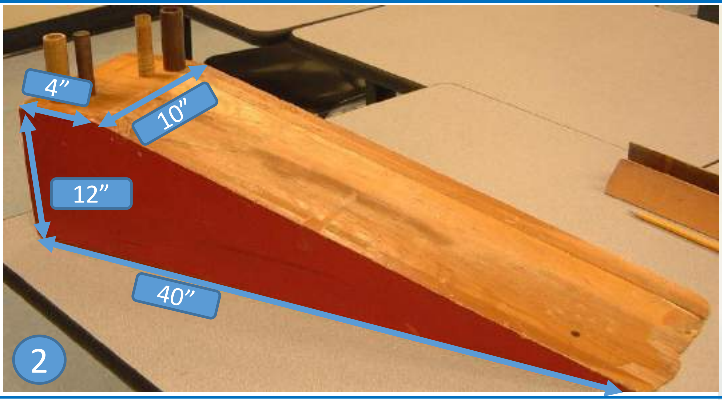
REQUIRED ITEMS

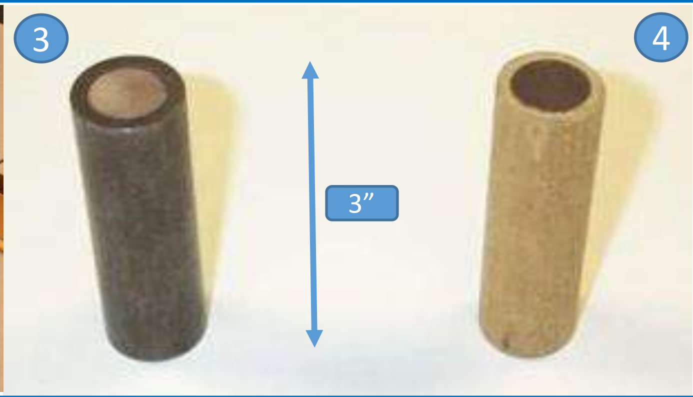
Item	Qty	Cost and Build Time	Description/Details
Inclined Plane	1	$40; 1 hour	An inclined plane able to support both rolling cylinders simultaneously. Approximate size is 12 inches high, 40 inches long, and 10 inches wide, which can be built with plywood and nails/screws. 2
“Steel Wheel”	1	$10; 45 minutes (machining req’d)	A steel cylinder of approximately 3” length and 1” diameter with a wooden core which weighs approximately the same as “Rolling Timber”. 3
“Rolling Timber”	1	$10; 45 minutes (machining req’d)	A wooden cylinder of approximately 3” length and 1” diameter with a steel core which weighs approximately the same as “Steel Wheel”. 4
12” Ruler	1	$1	This is used to start the race.

APPLICATION

<u>Before Class</u>: Obtain the materials. Measure and calculate the basic parameters (mass, diameters). Practice the demonstration.

<u>In Class</u>: First establish the scenario by introducing and describing “the players” in your best race announcer’s voice. Then, without any analysis, ask the students to guess which “player” will win the competition. Ensure you record this on the board. Build up to the start of the race and stop just short of letting them go. Ask students to consider if weight might be a factor affecting the outcome, then provide the class with the weight of each player and see if their guesses change (record on the board). Again, build up to the start and stop short to discuss the concept of mass being a resistance to translation and moment of inertia as resistance to rotation. Have students help you calculate the moment of inertia for each of the players and take a final tally of the bets. Finally, let the race happen!
Observations: The student should observe that the outcome is a factor of the moment of inertia and not the weight (given the overall dimensions and the weight of the players are approximately the same).





<u>Additional Application</u>: Hype up the event by dramatizing the race! Consider using racetrack videos and noises which can easily be found on the internet. Ask students to guess which will win once the scenario is set up and before the principles are discussed. Build suspense by working your way to the “gun shot” starting the race, then backing off the start to analyze another aspect. If you’re using Power Point, incrementally build your slides to build suspense! Also, cylinders of different materials and diameters might be considered.

THE FERRIS WHEEL

DYNAMICS

Keywords: Fixed Axis, Kinematics, Rigid Body, Rotation

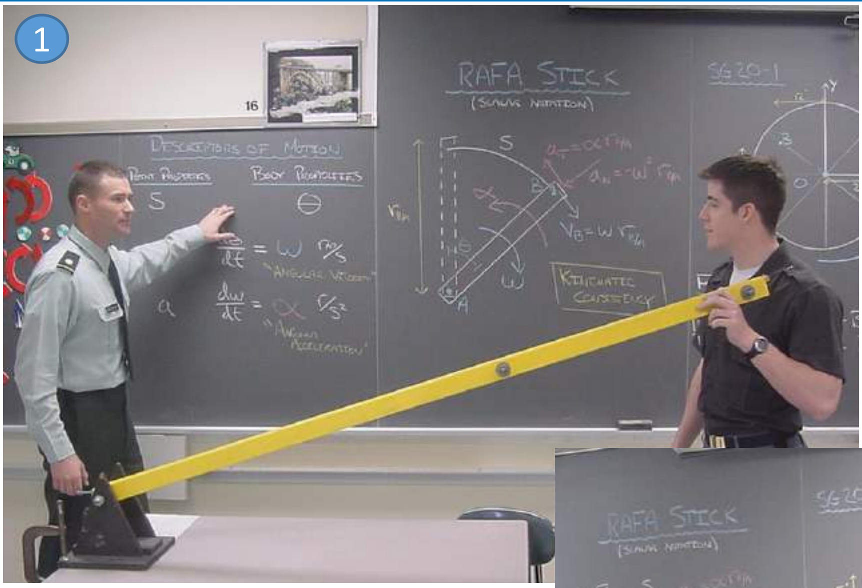
Submitted by: Tom Messervey

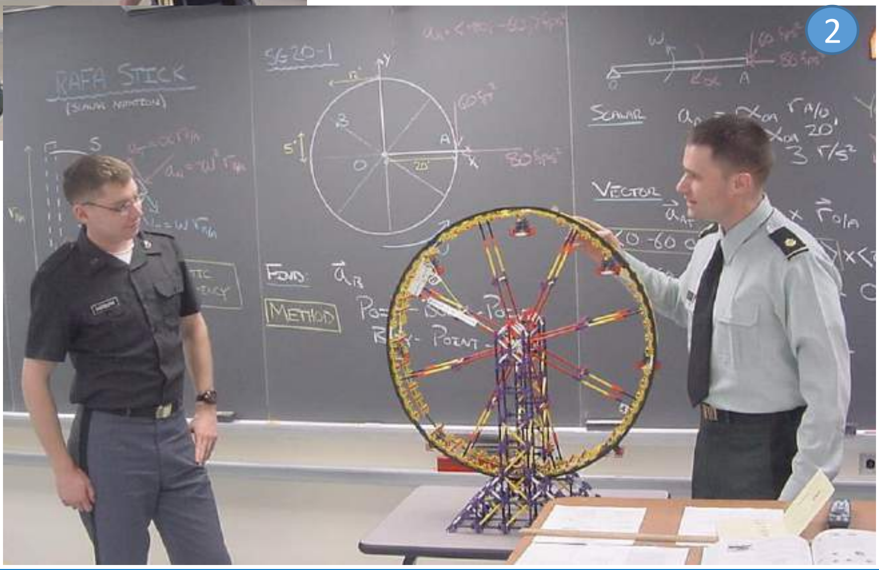
Model Description: This training aid demonstrates the rotational kinematics of a rigid body, the first step in rigid body kinematics problems. This demonstration should take 10-15 minutes.

Engineering Principle: Amusement park rides are a great example of and motivation for kinematic relationships. Here, a Ferris wheel provides an example of rotation about a fixed axis (RAFA). It is quickly shown for a rigid body that any two points on that rigid body can be joined by a "RAFA" stick. Using the RAFA stick, the following equations are developed.

$$v = \omega \times r \qquad \alpha = Angular\ Acceleration$$

$$a = \alpha \times r + \omega \times (\omega \times r) \qquad \omega = Angular\ Velocity$$



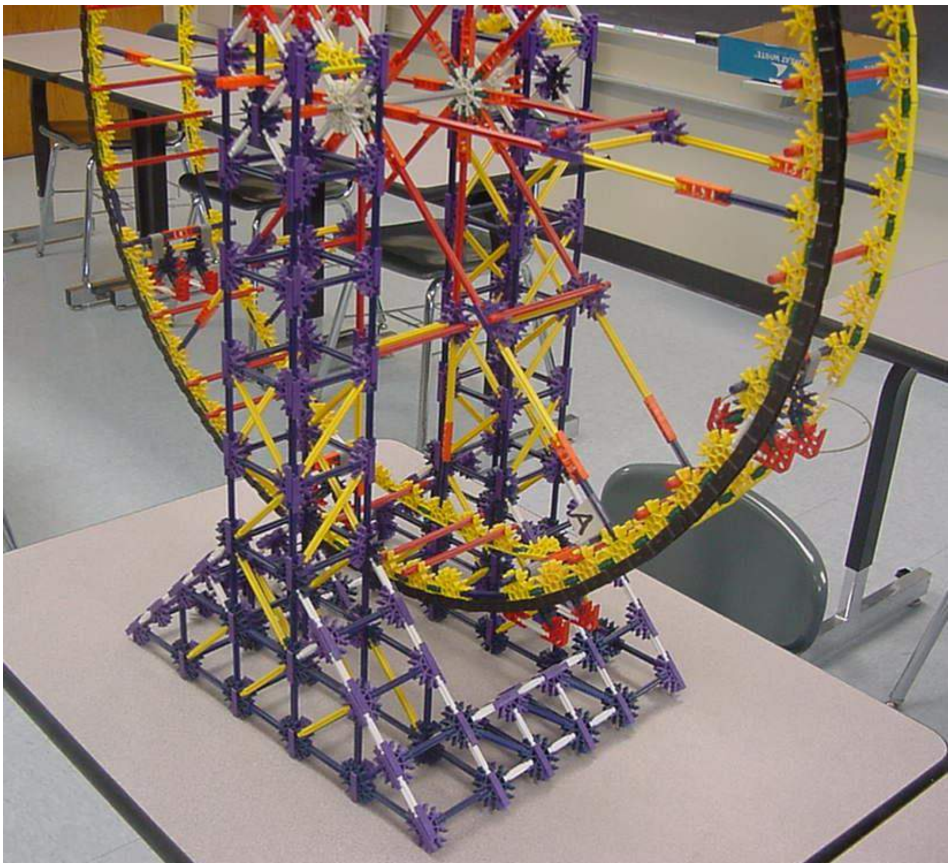


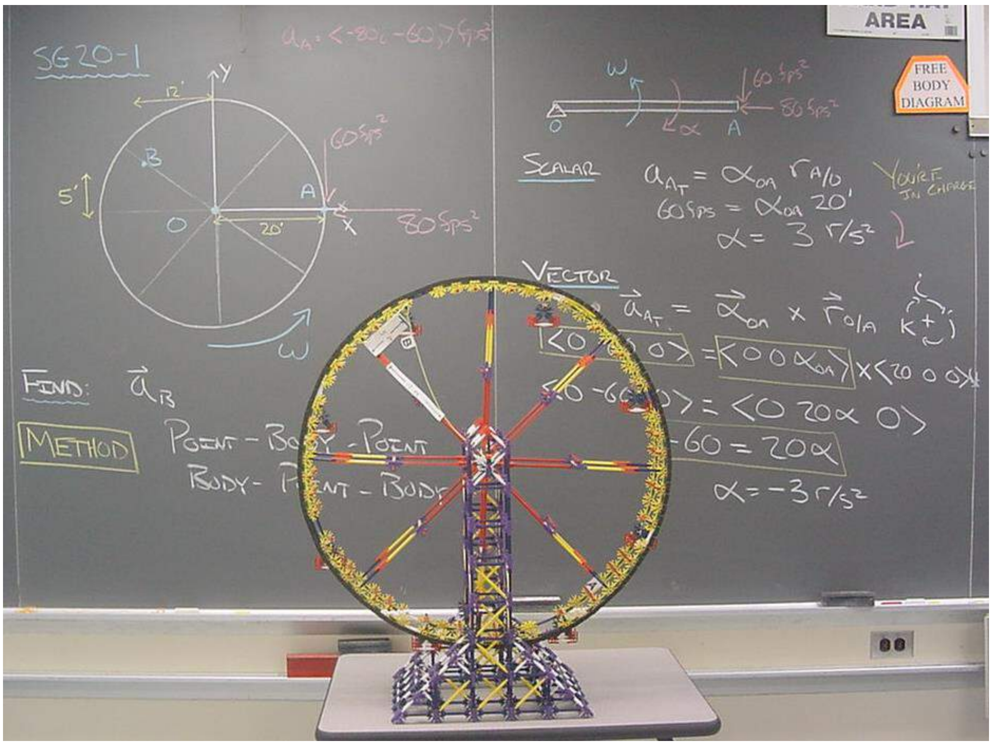
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
RAFA Stick 1	1	\$15-50 depending on size and material; 25 minutes	Any size stick, pinned on one end, and clamped to a desk.
Ferris Wheel 2	1	\$20-50; 45-60 minutes for KNEX	Any toy model will work, as well as the KNEX version used in this example.

APPLICATION

Before Class: RAFA stick construction is a board bolted to a wooden base shaped like the textbook illustration representative of a pinned support. This same training aid is also utilized in our statics block with a roller under (wooden wheel) the free end to show a simply supported beam. The KNEX Ferris wheel takes a little more effort, but also serves as a great display in the hallway or classroom. A few blow-up photos are included below.





In Class: The Ferris wheel is quickly introduced as the motivation for the material and the RAFA stick is then utilized to develop the theoretical equations. The RAFA stick is also nice because it is very easy to demonstrate and “see” the difference between point and body properties, ie. - how the angle any part of the stick moves through is the same, but the distance traveled by your hand as it is placed further from the base increases. The Ferris wheel then is utilized to complete the lesson with an example problem by examining the velocity and acceleration of two different points on the wheel. Data is provided for one point and the information desired is about a different point.

FLUIDS

FLUID PROPERTIES

FLUIDS

Keywords: Density, Mass, Resistance, Viscosity, Volume

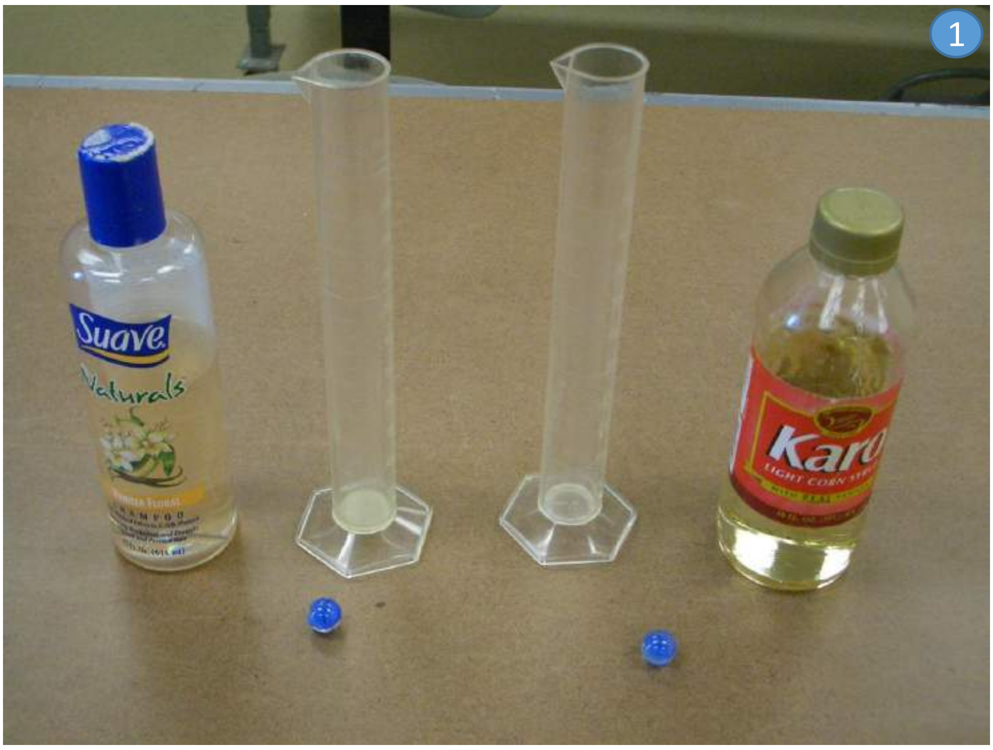
Submitted by: Justin Highley

Model Description: This is a simple demonstration of the difference between density and viscosity in fluid mechanics. Two equal size containers, one containing shampoo and the other corn syrup, are used to show the difference between the two concepts. This demonstration should take 5-8 minutes.

Engineering Principle: Most students are familiar with density and viscosity separately, but erroneously assume the two are always related. Density is simply mass over volume, and can be thought of as the "heaviness" of a material. Viscosity (μ) is a measure of a fluid's resistance to flow and is used to relate shear stress to the rate of deformation:

$$\tau = \mu \frac{dV}{dy}$$

In general, as viscosity increases, so does density. However, in this demonstration the denser liquid (corn syrup) is less viscous than the less dense shampoo. This demonstration serves as a good lead into a discussion of viscosity as an independent property. 1



REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Graduated Cylinder	2	$20	They must be of equal height.
Shampoo	1	$3	Not that much is needed and the material can be recycled when complete.
Corn Syrup	1	$3	Not that much is needed and the material can be recycled when complete.
Marbles	2	$4 for a pack	The two used must be the same size and weight.
Scale	1	$15	Optional

APPLICATION

Before Class: Fill each graduated cylinder with equal amount of shampoo and corn syrup. Have the marbles in your pocket or readily available.

In Class: Pour equal amounts of corn syrup and shampoo into the cylinders. You can either use the scale to weigh the cylinders and prove that the corn syrup is more dense, or simply tell them. Then show them the marbles and tell them you are going to simultaneously drop a marble in each beaker. If desired, you can measure the marbles to demonstrate they are the same weight. Ask the students to predict which marble will reach the bottom first. Most will state that the marble in the shampoo will hit first because it is the less dense fluid. You can play up the demonstration by having 1-2 students time the corn syrup beaker and others time the shampoo beaker. When you release the marble, the corn syrup marble will fall quickly, while the shampoo marble will take considerably longer – the difference will be obvious.

Observations: The students should observe that a denser fluid is not necessarily more viscous. After the demonstration, you can show this by pouring the fluids out into jars. This demonstration can then transition into the discussion of Newtonian fluids. If the demonstration will be repeated in back to back classes, have enough materials for 2 demonstrations since emptying the shampoo/corn syrup back into their containers can be a messy affair. Also, cleaning the marbles sufficiently to put them back into your pocket can be time consuming as well.

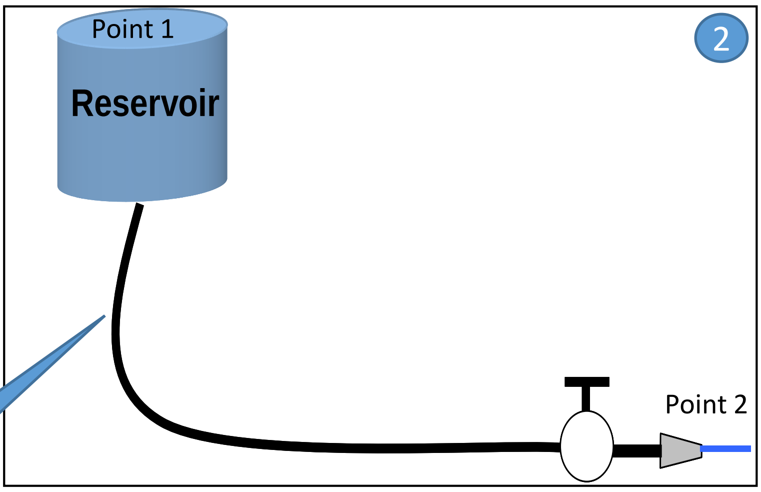
HEAD LOSS

FLUIDS

Keywords: Bernoulli Equation, Energy Equation, Head, Inviscid, Pipe Flow

Submitted by: Justin Highley

Model Description: This is a demonstration used to show the effects of head loss in pipe flow. A large water container (bucket or drum) with a hose is placed at a known elevation. 1 Different nozzle diameters can be used to demonstrate the effects of minor losses on pipe flow. This demonstration should take 15-20 minutes.



Engineering Principle: The energy equation is the primary solution tool used in pipe flow.

$$\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1+h_P=\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2+h_T+h_L$$

For inviscid fluids with no losses, this equation simplifies to the Bernoulli equation:

$$p_1+\frac{1}{2}\rho V_1^{\,2}+\gamma\, z_1=p_2+\frac{1}{2}\rho V_2^{\,2}+\gamma\, z_2$$

In this demonstration the Bernoulli equation is used to predict the ideal (maximum) velocity from the hose. This is done by applying the equation between the top of the water container (Point 1) and the hose nozzle (Point 2). 2 To simplify the analysis, several assumptions are made:

Point 1 is a free surface: p_1 and $V_1 = 0$.
The water exits as a free jet: $p_2 = 0$.
The hose nozzle is at the zero datum: $z_2 = 0$.

Therefore, for the above system the velocity at the nozzle can be found by:

$$V_2=\sqrt{2gz_1}$$

Again, this is the ideal velocity and neglects any losses in the system.
By finding the actual velocity as described later one can calculate the head loss in the system. Returning to the energy equation and applying the same assumptions as before, head loss is given by:

$$h_L=z_1-\frac{V_2^2}{2g}$$

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Large bucket or drum (10L or more)	1	$25	The container must be vented to the atmosphere at the top and have a spigot for attaching a hose.
Hose	1	$20	Typical garden hose
Nozzle	Various	$5-20	It is best to have at least two different sizes.
Spigot	1	$15	This can be at the reservoir or hose end.
Stop Watch	1	$5	
Bucket	1	$5-10	The bucket must be accurately labeled so that it can measure volume. Verify any manufacturer markings.
Graduated Cylinder	1	$5	

APPLICATION

Before Class: Set the reservoir in a secure overhead position (6-8 feet high), ensure that the reservoir is filled and select a nozzle for the first demonstration. Have the bucket and graduated cylinders ready for the demonstration. Make sure to do a test run to ensure no leaks are present and to check that the math works as expected for your particular setup. The first setup will take up to an hour.

In Class: Show the students the setup and have them apply the Bernoulli equation to predict the maximum theoretical velocity from the hose. Once they have a value, open the spigot on the reservoir (1-2 mins depending on the size of your water tank – an 11 liter tank yields about 4 minutes of flow) and drain the water into the bucket. After a sufficient amount of time, measure the volume of water and calculate the volumetric flow rate *as Q = Volume/Time* and the velocity as *V = Q*Area*, where the area is the cross-sectional area of the nozzle outlet. Compare this value to that predicted by the Bernoulli equation – it will be significantly less.

Explain that the difference is due to the inviscid assumptions in Bernoulli, and that the energy equation analysis is more accurate. Then calculate the head loss using the equation given above . Repeat the experiment using other nozzles. The value of head loss will change due to the different minor losses.

Observations: By comparing the actual velocity to the ideal, the students should observe that the Bernoulli equation is limited in its applications. Additionally, they will learn that the inviscid assumption overly simplifies pipe flow analysis.

Additional Application: Place the reservoir close to a hose and water source. This will allow you to rapidly refill the tank between demonstrations. Also, since velocity and head loss are functions of elevation, maintain the hose nozzle at a fixed height while discharging to ensure consistent results.

HYDROSTATICS

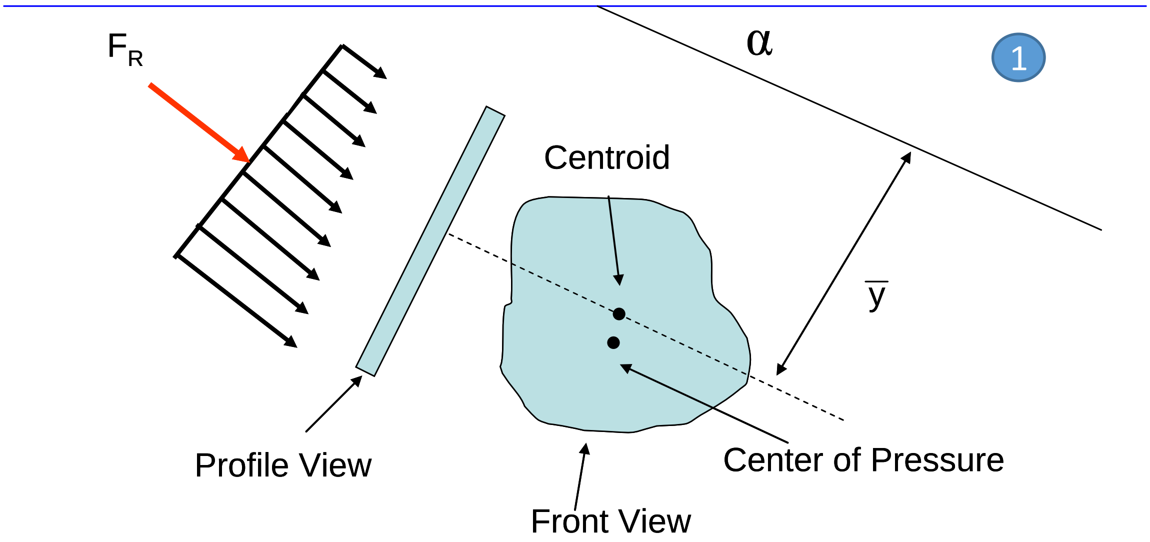
FLUIDS

Keywords: Fluid Pressure, Submerged Plane

Submitted by: Justin Highley

Model Description: This is a demonstration that helps students visualize the effects of fluid pressure on various surfaces. Various cutout shapes are used, including plane and curved surfaces, which are submerged into a fish tank during the derivation of the hydrostatic pressure equation. This demonstration should take 8-10 minutes.

Engineering Principle: Hydrostatic forces acting on a submerged plane surface are linearly distributed over the surface, and act at the center of pressure rather than the centroid of the object. Most textbooks include a picture similar to the figure below, which is a view looking down upon an object placed into the fluid at an angle. The geometry and orientation is often hard for students to grasp, so this demonstration makes it easier for them to conceptualize. Below is a hydrostatic pressure distribution. 1



Calculating the magnitude of the resultant force is straightforward using the hydrostatic pressure equation.

$$F_R = \gamma \bar{h} A$$

where:

F_R = Resultant force
γ = Specific Weight of the fluid
$\bar{h}$ = $\bar{y}$sinα = Vertical distance from the surface to the centroid
A = Object's surface area

Finding the location of the resultant force is more difficult, but is done using the equation

$$y_{CP} = \bar{y} + \frac{\bar{I}}{\bar{y}A}$$

where:

y_{CP} = Slant distance from the surface to the center of pressure
$\bar{y}$ = Slant distance from surface to the centroid
$\bar{I}$ = Moment of inertia

The difficulty with the derivation comes in differentiating between the various geometry measurements: $\bar{h}, \bar{y}, and\ y_{CP}$.

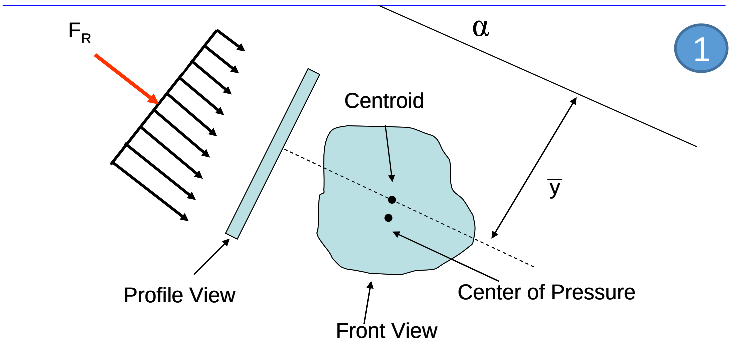
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Fish tank	1	$45	It must be large enough to fit in the cutouts.
Plastic cutouts representing plane and curved surfaces	Various	$10; 20 minutes	Use different shapes and sizes. Ideally, one cutout is shaped like the object in the drawing/figure used during the derivation (like above).

APPLICATION

Before Class: Fill the fish tank and have it on a rolling cart if possible. This will enable it to be placed in a prominent position during the actual demonstration.

In Class: When doing the derivation and discussing the differences between $\bar{h}, \bar{y}, y_{CP}$, take one of the cutouts and insert it into the fish tank. If a picture similar to 1 was used in class, stand on the side of the tank and insert the cut out so that the students see only the profile view. Explain that what you are seeing is the front view from the picture on the board. Also point out the angle α (angle between the surface and the surface) from this vantage point.



Next, discuss the difference between the various measurements. The "y" distances are slant lengths, and run along the surface of the object, whereas the "h" measurements are vertical distances from the water surface.

Observations: Students can visualize the pressure distribution along a submerged surface and see the difference between the various geometric measurements associated with hydrostatics.

Instructor Tips: The curved surface cut outs can also be used to demonstrate the projected area of a section of fluid when dealing with submerged curved surfaces. Additionally, they help in visualizing the "cut out" section when calculating its volume.

INTERNAL FLOW AND LOSSES

FLUIDS

Keywords: Conservation of Mass, Flow Regimes, Moody Chart, Volumetric Flow Rate

Submitted by: Richard Melnyk

Model Description: This is a simple demonstration of the basic principles of internal fluid flow and can also cover major losses. The demonstration can cover concepts such as conservation of mass, volumetric flow rates, flow regimes, use of the Moody Chart and major head losses. This demonstration should take 10 minutes.

Engineering Principle: Internal flow is based on fluid moving through a pipe, duct or conduit. It is something we all experience in everyday life and do not think about. Instead of working on a sample problem in class with no physical relevance, this demonstration reinforces the basic principles of pipe flow, including volumetric flow rate, Reynolds number, friction factor and head loss. The basic equations required are:

$$Q = \frac{V}{\Delta t}$$ Volumetric Flow Rate

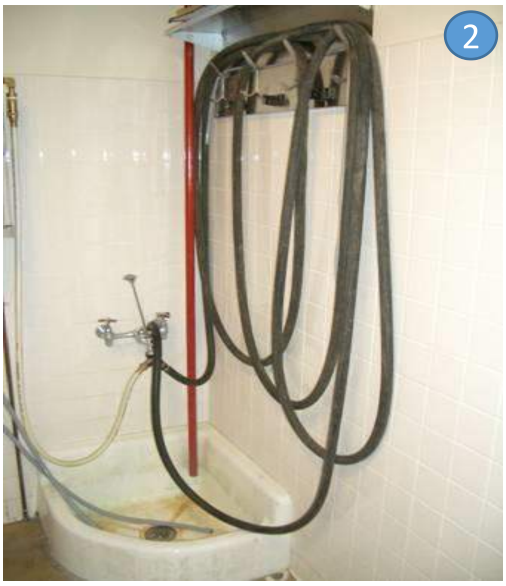
$$V = \frac{Q}{A}$$ Mean Flow Velocity

$$Re = \frac{\rho V D}{\mu}$$ Reynolds Number

$$h_L = f\ \frac{L}{D}\ \frac{V^2}{2g}$$ Head Loss (obtain friction factor from Moody Chart)

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Bucket 1	1	$5	Bucket must be accurately labeled so that it can measure volume (check the manufacturer's marks to make sure they are correct!).
Hose 2	1	$15	Any garden hose will work
Ruler or micrometer	1	$5-15	Used to measure the inside diameter of the hose.
Stopwatch	1	$5	Used to measure the time to fill the bucket to a pre-selected volume.



APPLICATION

Before Class: Find a utility closet or faucet where you can connect the hose to a water source. Measure the length of the hose and diameter unless they are already known from the manufacturer.

In Class: Move the class to the area of the water source. This may require a short trip down the hall or outside. If necessary, have students operate the hose, faucet, and watch. Turn on the water and time how long it takes to fill the bucket to a predetermined volume. When this is complete, move back into the classroom. From this point, the students can calculate many different parameters with simple data obtained during the experiment. Using the equations listed above students can calculate the volumetric flow rate and mean velocity. With data tables on water properties, they can calculate the Reynolds number for the flow. With a Moody diagram and information about the hose material, they can then determine the friction factor and calculate head losses.

Observations: Students will get a better sense of what a certain volumetric flow rate and velocity looks and sounds like. Often students do not have a sense of how ‘fast’ or ‘slow’ a volumetric flow rate is. They will also understand what constitutes turbulent flow as the water will likely be turbulent if it fills the entire hose (required for internal flow analysis).

Additional Application: If more accuracy is desirable, a thermometer can be used to measure the temperature of the water. This will help determine the density of the water to calculate the Reynolds number. In addition, you can add minor losses by accounting for any junctions, fittings, or valves along the flow. Finally, to enable students to see how changing the diameter of the hose affects parameters such as Reynolds number and losses, you can use a smaller or larger hose and repeat the experiment.

SMOKE TUNNEL

FLUIDS

Keywords: Flow Visualization, Laminar, Turbulent, Separation

Submitted by: Justin Highley

Model Description: This is a series of demonstrations using a smoke tunnel for flow visualization, including laminar/turbulent flow and separation. This demonstration should take 10-15 minutes.

Engineering Principle: This demonstration can be used in the context of several lessons, including external flow, Computation Fluid Dynamics (CFD), and lift/drag.

External Flow/CFD: Properties within a flow field vary depending on whether the flow is laminar or turbulent. Laminar flow properties can be found using either the Bernoulli equation (inviscid flow) or the Navier-Stokes equations (viscous flow). The Navier-Stokes equations struggle with calculating turbulent flow properties and most often these flows are found using CFD. Part of the reason is the unpredictable and random nature of turbulent flow.

Lift/Drag: The lift created by an airfoil varies as a function of angle of attack - as the angle increases, so does the lift. However, at the critical angle of attack, the flow will separate from the airfoil with a corresponding drop in lift and increase in drag. Drag on an object is due to changes in pressure across a body. As the flow approaches a body, a stagnation point is formed and the flow is zero. As the flow moves away from that point, the velocity increases, thereby causing the pressure to decrease (Bernoulli). This is the cause of pressure drag, which is the dominant form of drag on objects.

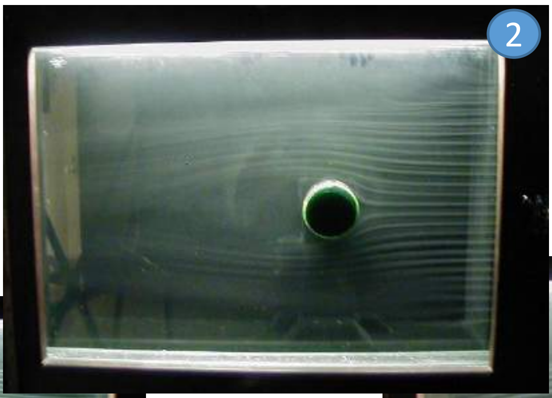
REQUIRED ITEMS

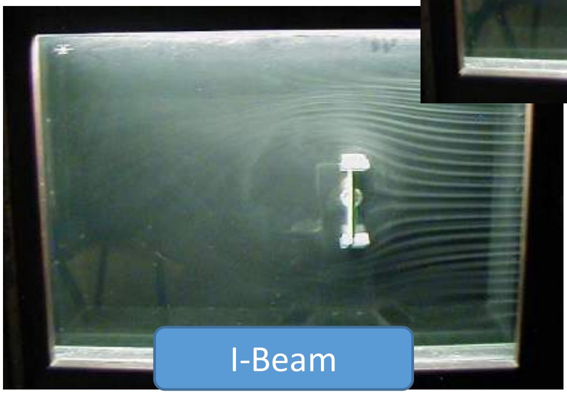
Item	Qty	Cost and Build Time	Description/Details
Smoke Tunnel 1	1	Thousands	Models vary based on capabilities desired and cost.
Shapes to put in the Smoke Tunnel	Various	$25	Common shapes include airfoils, cylinders, and flat plates.

APPLICATION

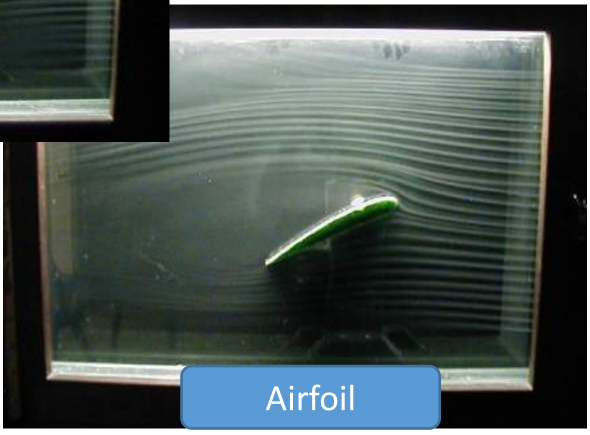
<u>Before Class</u>: Put the first shape you plan on using into the smoke tunnel. If required, warm up the smoke generator.

<u>In Class</u>: *External Flow:* For this class, the demonstration is best done toward the end of class, depending on the location of the smoke tunnel relative to the classroom. Normally the best shapes to use are a cylinder and a flat plate (normal to the flow). The flow around the cylinder 2 will enable the students to see how the flow conforms to the shape of the body, until it separates as the body's geometry turns away from the flow. Slowly increase velocity and point out how the separation point moves further back on the cylinder.





I-Beam



Airfoil

For the flat plate, the flow will initially stagnate at the front, but will move to the top and bottom of the plate. Because the plate is normal to the flow, the drag force is due to the pressure only – there is no skin friction (shear stresses are not in the flow direction). Once you are established in the turbulent flow regime, point out how the different eddies develop in the flow, and that no two are alike (i.e. random). Reinforce how the unpredictable behavior makes it hard to analyze properties in the turbulent flow regime.

Regardless of the shape used in the smoke tunnel, the students should be able to see the stagnation point at the front of the body. They should also be able to see that as the flow moves away from that point, the velocity increases. They won't be able to see the decrease in pressure, but they know it's there based on Bernoulli.

<u>CFD</u>: Unlike the other two classes, it is best to begin this class at the smoke tunnel, pointing out the random nature of the eddies during turbulent flow. Use this as a lead-in to the discussion of the need for CFD to analyze turbulent flow, which is significantly more complex than laminar flow.

<u>*Observations*</u>: In each demonstration, the students can obtain a better idea of what is happening as the flow moves over bodies of various shapes and sizes. The capabilities of the specific smoke tunnel will determine the extent of the student's learning experience.

<u>*Instructor Tips*</u>*:* Use as many of the different shapes in the smoke tunnel as possible so the students see the effects that geometry has on the flow field. Particularly, the use of different shapes can precipitate the discussion of how streamlining is used to delay separation and therefore reduce pressure drag.

THE FISH TANK

FLUIDS

Keywords: Continuous Substance, Fluid, Shear Stress, Volume

Submitted by: Justin Highley

Model Description: This is a demonstration that uses a fish tank to reinforce the definition of a fluid and some of the important physical characteristics associated with fluids. This demonstration should take 3-5 minutes.

Engineering Principle: A fluid is defined as a substance that continuously deforms when subjected to a shear stress. Additionally, the molecular spacing in liquids is essentially constant and therefore a given mass of liquid occupies a certain volume of space. That volume will fill the container in which it is placed. Finally, when analyzing the behavior of fluids, they are normally treated as a continuous substance, or a continuum. This eliminates the requirement to treat each fluid molecule independently, and allows one to deal with the average properties instead.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Fish Tank	1	$40-75	A large open surface is preferred. 1
Fan	1	$10	The fan must be powerful enough to ripple the water surface, but small enough to be handled by the instructor. 2

1

2

APPLICATION

Before Class: Fill the fish tank and have it on a rolling cart if possible. This will enable it to be placed in a prominent position during the actual demonstration. It must be close enough to the wall so the fan can be plugged in and reach the tank, unless you are using an extension chord as well.

In Class: After discussing the definition of a fluid, ask the class what types of shear forces exist in nature. Most will answer "gravity," but some may mention wind which can lead into the use of the fan. Alternatively, pull out the fan and ask them what kind of force you could create with it – lead them into answering "shear stress." Ask the students what will happen when you turn on the fan and place it (horizontally) above the water. Common sense should tell them that it will deform or ripple. Turn the fan on and let them watch the surface deformations occur. 3

You can also reinforce the concept of liquid fluids occupying a fixed volume. Discuss why the water takes on the shape of the fish tank.
When discussing the concept of a continuous fluid, point out that while the viscosity, density, specific weight, etc. of each water molecule may vary slightly based on its location in the tank, the differences are insignificant and the average properties are almost always used.

Observations: Students will see the water surface deform as a result of the shear stress imparted by the fan.

Additional Application: The deformation of the water surface can also lead into a discussion of viscosity as a measure of resistance to deformation (i.e. "What would happen if I replaced the water with honey and turned on the fan?")

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HEAT TRANSFER

ICE MELTING BLOCKS

HEAT TRANSFER

Keywords: Conservation of Energy, Fourier's Law, Phase Change, Thermal Conductivity

Submitted by: Gunnar Tamm

Model Description: This demonstration illustrates the material property of thermal conductivity, and how this property affects conduction heat transfer in a solid. Concepts include Fourier's Law, conservation of energy and solid-liquid phase change. This demonstration should take 8-10 minutes.

Engineering Principle: Fourier's Law states that the heat transfer rate in a solid is proportional to the thermal conductivity, k, cross sectional area, A, and temperature gradient of the material. At the surface, assuming the x-direction is into the solid,

$$q_x = -kA\left.\frac{\partial T}{\partial x}\right|_{\text{surface}} \qquad (1)$$

For two similar solid blocks at the same room temperature, the block with the higher thermal conductivity will "feel" colder to the touch, because thermal energy is more readily taken from your hand (heat source) into the block. Likewise, if a colder sink is placed into contact with the two blocks, the material with higher thermal conductivity will transfer thermal energy out of the block faster.

Unless a steady condition has been achieved, the two blocks will change temperature at different rates according to

$$q = mc_p\frac{\partial T}{\partial t} \qquad (2)$$

where the rate of heat transfer, q, is proportional to the mass, m, specific heat of the material, c_p, and the rate of temperature change with time.

The block with the higher thermal conductivity will more rapidly lose thermal energy to the cold sink, producing a greater temperature change of the block with time. This is valid if both blocks have comparable heat capacity rates (mcp). The latent heat of fusion of water is demonstrated by melting ice cubes on the two blocks. The block with the higher thermal conductivity will be able to melt the ice faster. The energy input rate required to melt ice is given in terms of the latent heat of fusion and rate of mass changing phase as

$$q = \dot{m}h_{fg} \qquad (3)$$

Engineering Principle: From the rapid melting using the high thermal conductivity block, the demonstration also illustrates that the heating of the ice cube by the ambient air through convection is insignificant compared to the heating of the ice cube via conduction from the block. For the lower thermal conductivity block, which serves to insulate the ice cube bottom, the conduction and convection rates are of a comparably small scale.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Blocks of different materials Beam	2	$2-7 depending on size; 25 minutes	Must sit with level top surfaces; should be the same size, and big enough to hold an ice cube; one with high (copper is best, brass, aluminum) and one with low (rubber, plastic, wood) thermal conductivity; can be painted the same color for concealing the type of material
Ice cubes	2		Cold enough so no melting has begun before experiment.
O-rings or rubber bands	2	$1-3	Keeps ice and melted water from falling off top surface.
Stopwatch	1	$5	Can be used to “take bets” on how long it’ll take to melt the ice.
Scale (optional)	1	$15	Measures the mass of blocks and ice cubes.

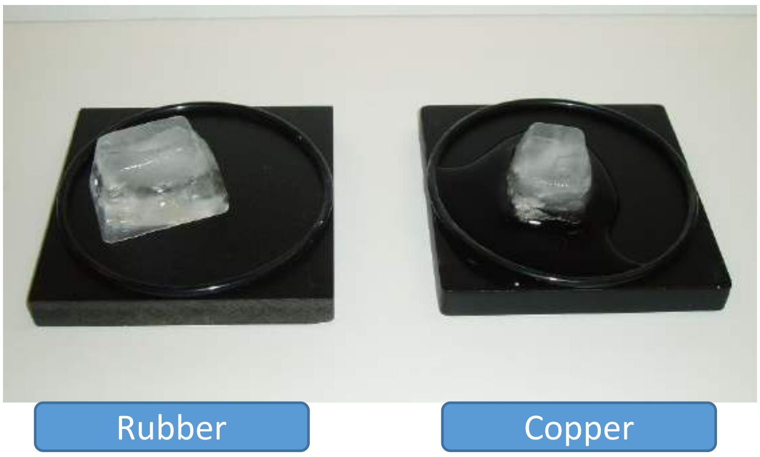
APPLICATION

Before Class: Have two ice cubes ready, at below freezing temperature. Keep in an insulated container to prevent any melting before the demonstration. Allow the two blocks to sit in the same space for some time so that they come to the same equilibrium temperature.

In Class:
(a) Ask volunteers to feel the two blocks to determine which one is colder. The block with the higher thermal conductivity (copper is the best), will feel colder than the block with the lower thermal conductivity (eg. rubber) even though they are at exactly the same temperature
(b) Before bringing out the ice cubes, ask which block would melt an ice cube faster. Some will undoubtedly guess the low-conductivity bloack, as it feels warmer. “Take bets” as to how long it’ll take to melt an ice cube on each one. With timer ready, place an ice cube onto each block. The copper will melt the ice cube dramatically faster, dancing on the pool of melt it has formed, while the ice cube on the rubber block does nothing. Note that without any boundary, the ice cube on the copper block will not necessarily slide off of the level block. Surface tension will keep it from doing so.

In Class:

After 1 minute, the photos show the difference in melting rates, with the insulating block having little effect on the ice cube. The ice cube is melted within a matter of 2-3 minutes on the high thermal conductivity block, while remaining relatively unchanged on the insulating block.



(c) After the copper has melted the ice cube, circulate both blocks once again. The copper block will feel much colder as it has lost more thermal energy. The copper block will feel cold for some time, which will show how latent heat can be large as compared to sensible heat. With the time and initial mass of ice cube known, the average heat transfer rate from the copper block can be calculated according to equation (3). The temperature of the block can be estimated then using equation (2) if the mass of the block is known. This assumes other heat transfer from the block is negligible.

Additional Application:

a) Before starting, ask for an explanation of why something feels cold or warm. Establish with the class that you do not feel temperature, but rather temperature differences and the heat transfer that results.

(b) The ice melting can have all of the excitement of a race, even with copper being the clear winner. Take bets, and ham it up!

(c) A discussion can follow regarding the spatial variation of temperature in the blocks, due to the different thermal conductivities. This may be a good lead-in into a lesson on lumped capacitance.

(d) Discuss thermal losses to account for all energy transfers to and from the block, and stored energy change of the block. An expression for conservation of energy can be obtained for the block as

$$\dot{E}_{in} + \dot{E}_{generated} = \dot{E}_{out} + E_{stored}$$

where the energy input is from the air via convection and table underneath the block via conduction, which are both warmer once the block begins to cool. There is no energy generation. The energy output from the block is to the ice and ice-melt, which are both colder, mostly as latent heating of the ice in equation (3) but also as sensible heating as given by equation (2). The stored energy of the block is given by equation (2) for a block with uniform temperature. This will be a negative term.

PARABOLIC CONCENTRATOR

HEAT TRANSFER

Keywords: Concentration, Energy, Heat Flux, Radiant, Reflection

Submitted by: Gunnar Tamm

Model Description: This demonstration illustrates how to concentrate radiant energy, solar or other, using a parabolic reflecting dish to produce high enough heat fluxes to burn paper. This demonstration should take 10 minutes.

Engineering Principle: The sun is located far enough from the earth that radiation arrives here in nearly parallel beams. A parabolic dish will spectrally reflect the parallel beams towards the focus of the dish, greatly amplifying the radiation intensity of the original beam. In doing so, anything placed into the focus of the dish will incur much more power per unit area than the original beam, such that an object at the focus may reach very high temperatures.

For indoor convenience, a spotlight can be used with a high candlepower rating. The candlepower rating is usually based on the brightest spot in the non-uniform beam of the spotlight. Although it is known that the sun can provide roughly 1000 [W/m^2] on a sunny summer day, conversion of the spotlight candlepower rating to actual radiant power flux [W/m^2] is not accurate without either measurement or the manufacturer's data. A 15,000,000 candlepower spotlight is used as it is the largest battery powered spotlight currently on the market, available from various manufacturers.

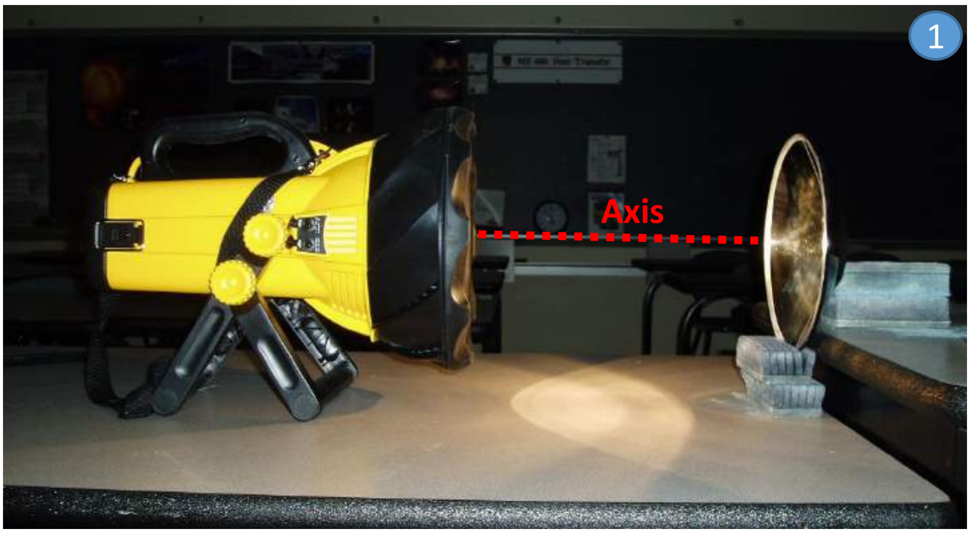
The concentration of light depends on the precise geometry and surface properties of the mirror. The more parabolic and reflective the surface, the sharper the focus will be. More light will be focused for a larger beam diameter, and mirror aperture to match.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
15,000,000 candlepower spotlight	1	\$60-100	Available from various manufacturers. The one shown has an aperture diameter of 8 ¾ ".
Parabolic Mirror	1	\$45	Highly reflecting parabolic surface, with aperture diameter approximately that of the spotlight. This mirror has an aperture diameter of 8 ¾ ".
Mirror Stand	1		Improvised materials. Goal is to align mirror axis with spotlight axis.
Paper / Match/ Tissue	1		Thin strip of any readily combustible material.
Thermometer / Thermocouple	1	\$15-35	Measures temperature at mirror focus.

APPLICATION

In Class: (a) The mirror and spotlight can be easily aligned either before or during class.



If the stand for the mirror is ready to go at a known height, the alignment will take half a minute. Above is an improvised mirror stand using chalk erasers. The spotlight comes with an adjustable stand. 1 The axis of the mirror should be the same as the axis of the spotlight for optimal concentration. The axial distance between the mirror and spotlight is arbitrary, but should not be too large. The alignment is fine tuned by observing the shadow of the mirror on the wall behind the mirror. In the image below, the spotlight beam diameter is slightly larger than the mirror diameter, showing a symmetrical eclipse image (mirror blocking light) on the wall. 2

(b) Ask for a volunteer to locate the hot spot of the mirror. This is done by moving a finger along the central axis towards the mirror. At the focus, the finger will rapidly get very hot on the side facing the mirror. Instinct will cause the student to remove the finger very quickly. ***CAUTION***: There is a risk of a being burned if the finger is kept in the focus too long, if a higher power spotlight is used, or if a better quality mirror is used. Try it first before the class does, and give fair warning to your volunteer!

(c) Once it has been proven that the focus is a hot spot, try burning a piece of tissue paper, match, or plain paper. At the focus, the paper will quickly smoke and even ignite! However, if the paper is even a little bit off the focus, it may not even smoke. The key is to zero in on the focus, which for this mirror is about 2-3 inches from the surface along the primary axis. This is best done by knowing where to look ahead of time, and by fine tuning the location by increasing the brightness of the spot on the paper as it is moved. This all assumes that the mirror axis is aligned well with the spotlight axis.

(d) Knowing that paper was burned, have students guess the temperature at the focus and then measure it with a thermometer or thermocouple.

Additional Application:

(a) After building up the hopes of the class that they will witness the incredible power of the sun, first take out a puny little 1,000,000 [cp] light. This will hopefully draw some "booing" from the class. Then get rid of the 1,000,000 [cp] light, and impress them by hauling out the markedly larger 15,000,000 [cp] light.

(b) Show images of solar concentrators being used in research and the power industry, either before or after the demonstration.

(c) If the concentrator is designed to collect heat, the useful heat delivery can be expressed as the radiant power reflected to the receiver which is positioned at the focus, less the thermal losses from the receiver to the ambient.

$$q_u = \eta_0 I_c A_a - U_c \left(T_c - T_a\right) A_r$$

where

$$\begin{aligned}
&q_u = useful\ \ heat\ \ delivered\ \ by\ \ the\ \ collector\ \ [W] \\
&\eta_0 = optical\ \ efficiency\ \ of\ \ the\ \ mirror,\ \ depending\ \ on\ \ surface\ \ properties \\
&I_c = irradiation\ \ on\ \ the\ \ mirror\ \ surface\ \ [W/m^2] \\
&A_a = aperture\ \ area\ \ [m^2] \\
&A_r = receiver\ \ area\ \ [m^2] \\
&U_c = overall\ \ heat\ \ transfer\ \ coefficient\ \ of\ \ the\ \ collector\ /\ receiver\ \ [W/m^2 \cdot K] \\
&T_c = collector\ \ temperature\ \ [K] \\
&T_a = ambient\ \ temperature\ \ [K]
\end{aligned}$$

The maximum temperature of the receiver (collector) can be estimated by setting the useful heat delivery to zero in the above expression. Concentrating solar power towers, like the one at Sandia National Labs, can achieve up to 5000 [K].

(d) The concentration ratio is defined as the area of the mirror aperture to the area of the receiver (collector) placed at the focus of the mirror.

$$CR = \frac{A_a}{A_r}$$

For a two-dimensional mirror (parabolic trough), the theoretical limit of concentration is 216 in air and 324 in glass. For a three-dimensional mirror (parabolic dish), the theoretical limit of concentration is 46,000 in air and 103,500 in glass. The highest solar concentration that has been achieved in the lab is 56,000!

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MATERIAL SCIENCE

BENDING A KNIFE BLADE

MATERIAL SCIENCE

Keywords: Annealing, Bending, Brittle, Deformation, Fracture, Rupture, Strength

Submitted by: Led Klosky

Model Description: Knife blades are typically very hard and brittle. In this rapid and inexpensive demonstration, the structure of a steel knife blade is transformed through simple heating and the blade becomes capable of sustaining large deformations without rupture. This demonstration should take 5-7 minutes.

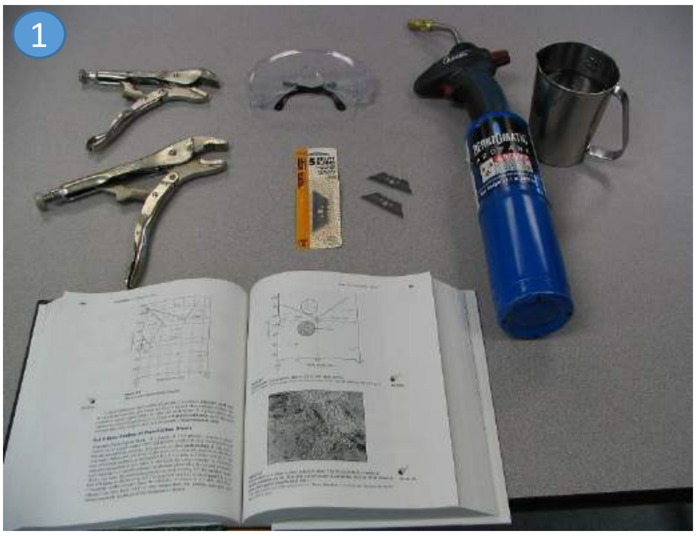
Engineering Principle: Knife blades are typically made of steels with relatively high carbon contents. These steels are also sometimes subjected to aggressive heat treatments which leave them exceptionally hard, strong and brittle. This is particularly true of utility knife blades, which are resistant to deformation (keeping them sharp longer) due to their hardness but have little toughness and thus rupture when subjected to large deformations. By heating the steel utility knife blade to an orange-hot state (perhaps 650 to 700 degrees Celsius), the steel is allowed to go through the initial stages of the annealing process, most likely leading to spheroid structure within the blade. It should be noted that this demonstration is qualitative rather than quantitative, since knowing the initial state of the blade in terms of carbon content or percent martensite, as well as what tempering and annealing went on during manufacturing, is very difficult to determine. Still, the demonstration brings out two key theoretical points. First, the heating and quenching of a sample will not lead to martensitic steels if the heat is insufficient for the formation of austenite. Second, very simple processes can lead to radical changes in material behavior, and engineers must be aware of these potential transformations when designing machines, especially for high-heat settings.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Vice Grips	2	$15 each	Vice grips (over pliers) ensure that the broken halves don't fly off into the gathered crowd.
Propane Torch	1	$25-50	A self-igniting torch works best.
Container of Water	1	$5	One pint is the minimum for quenching the sample. It doesn't need to be particularly cold, since the blade has little thermal mass.
Safety Gear	1 set	$15-25	Keep yourself safe
Utility Knife Blade	2	$1	Most simple utility blades will work; make sure to test them before class to ensure that the untreated blades break when bent, as not all blades are as brittle as you might like.

APPLICATION

Before Class: Make sure to test this one thoroughly before trying it in class. Different knife blades can behave very differently, depending on the manufacturing process. 1



In Class: Begin with the as-manufactured knife blade, and dig into the student's natural knowledge about the behavior. They should be able to guess what will happen when you grab the sample with the two pairs of vice grips and bend. Let them pick which blade to test, and show them that the blade snaps neatly after just a little bit of bending. 2 Then, take a fresh knife blade and heat it through with a propane torch while holding it with the vice grips. 3 During the heating, which should take less than 2 minutes, you can ask the students to give their thoughts on what is likely to happen. Having the phase diagram for steel displayed in the classroom can help fuel the discussion. The blade can then be quick-quenched in the water and the sizzling noise is good drama for keeping student interest. The blade cools almost instantly, and can then be bent back on itself without fracture. This demonstration is an excellent introduction to the topic of heat treating steels. It’s also a great way to illustrate that a mechanical designer must know about the heat treatment of steels to avoid unexpected behavior.

Additional Application: It is easy to relate this demonstration to what students might have seen in the old Western movies. Point out that a blacksmith making a horseshoe had to have a significant amount of knowledge about the heat treatment of steels (post 1870, anyway) in order to make a shoe that was both hard enough and tough enough to take the kind of beating that a galloping horse can dish out.

SHAPE MEMORY ALLOYS

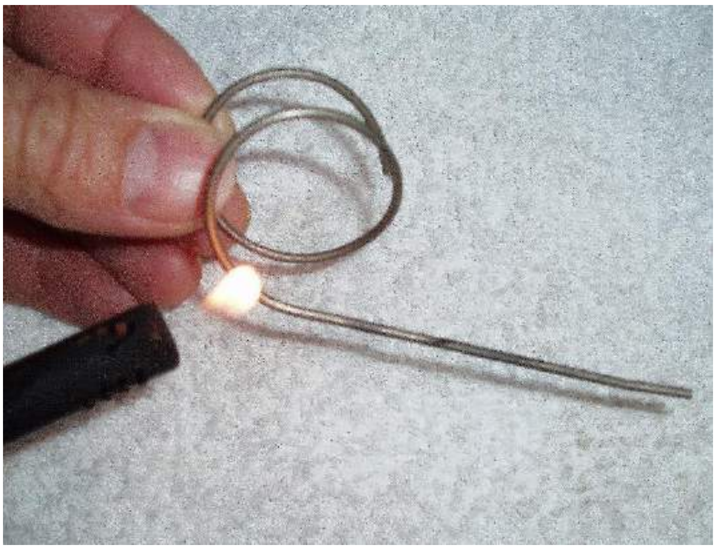
MATERIAL SCIENCE

Keywords: Deformation, Martensite, Nitinol, Superelastic, Undeformed

Submitted by: Victor Yu and Lanny Griffin

Model Description: These movie clips demonstrate the two phases of a shape memory alloy which enables shape memory alloys to "memorize" their pre-deformed shape, even after large deformations.

This demonstration should take 15 minutes.



Engineering Principle: The shape memory effect occurs due to a phase transition between the original, or memorized, austenite phase to a deformed martensite phase. Once a shape memory alloy is distorted into the deformed martensitic state, the material can "regain" its original austenitic shape if the material is heated to above its transition temperature. Nickel-titanium alloys, or Nitinol, allow up to 8 percent of recoverable deformation. When compared to steel, which only allows up to 0.8 percent of recoverable deformation, Nitinol has extremely large recoverable deformation which gives this material its truly remarkable properties. The transition temperature is approximately 150°F for the Nitinol used in the movie clips. This transition temperature can fluctuate from approximately -50°F to 300°F, depending upon the weight percent of each metal in the alloy.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Nitinol Sample	1	$13-15	An 8 inch wire sample of Nitinol is used to perform the activities demonstrated in the movie clips above. It is important to know the exact transition temperature of the alloy since the demonstration depends on this.
Lighter	1	$3	A standard household lighter to heat the deformed shape memory alloy above its transition temperature.
Clear Pan of Hot Water	1	$10	A container (larger than the Nitinol sample) which can hold water heated to a temperature that is approximately 5-10 °F above the transition temperature.

APPLICATION

Before Class: Heat the pan of water to a temperature of approximately 150°F using a Bunsen burner or any other heating source available. Ensure that the water temperature is adequate to induce the phase transformation between martensite and austenite. The water should be maintained at this steady state temperature until the time of the demonstration.

In Class: The different phases of a shape memory alloy, austenite and martensite, are discussed. In addition, the concept of the transition temperature is discussed and how the material can change from one phase to another based upon the transition temperature. We then show the students the sample of Nitinol and ask for a volunteer to deform the wire sample. The class is asked what phase the Nitinol sample is in after the volunteer has deformed the material. Then, with the heat resistant gloves on, the wire is heated with the lighter and the sample reverts back into its un-deformed, or austenite, shape. During the shape change, a discussion of phase changes is appropriate and the class is asked what phase the material is transitioning to with the application of heat from the lighter.

In a related experiment, the Nitinol is again deformed by a volunteer from the class. Ensuring that the pan of hot water is still at 150°F, the deformed Nitinol wire is dropped into the hot water. The Nitinol wire experiences a spontaneous transition where the wire "snaps back" into its undeformed, or austenitic, phase. Again, during the conduct of this related experiment, the same questions should be posed to the class (i.e. in what phase is the un-deformed wire, what phase is the Nitinol upon deformation, etc.).

Observations:

The students should observe the shape memory alloy returning back to its memorized shape after experiencing extremely large deformations. This demonstrates the shape memory alloy transitioning from austenite to martensite and back again by means of a thermally induced-recoverable phase transformation. The shape memory alloy returns to its un-deformed state since the material is heated above its transition temperature. The heat serves as a source of energy to transform the lattice structure which leads to a phase change from martensite to austenite. This phase transformation can also be induced by stress – the so-called super-elastic effect.

The superelastic behavior of Nitinol is used in the design of stents. The transformation temperatures are set to be slightly below body temperature. The superelastic effect is caused by the stress-induced formation of some martensite above its normal temperature. Because martensite has been formed above its normal temperature, the martensite reverts immediately to un-deformed austenite when the stress is removed. This process provides the elasticity in these alloys for strains up to about 8%. A common application of the super-elasticity in Nitinol is seen in eye-glass frames which can experience large deformations without breaking.

CREEPY PLASTIC

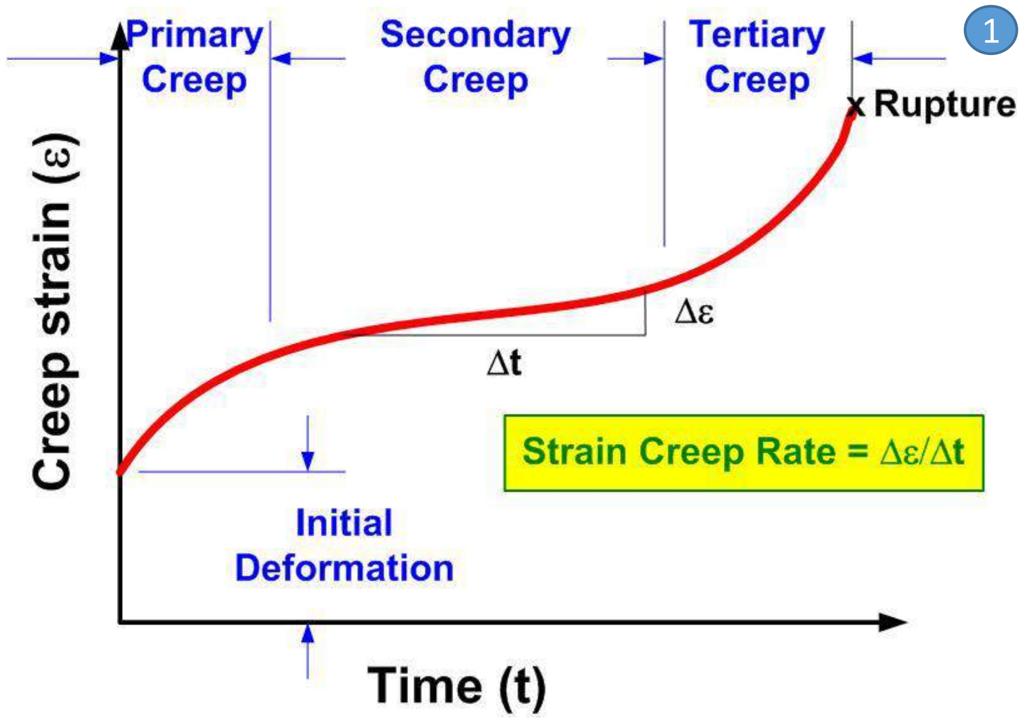
MATERIAL SCIENCE

Keywords: Deformation, Primary Creep, Rupture, Secondary Creep, Strain, Stress

Submitted by: Allen Estes and Led Klosky

Model Description: This is a simple demonstration to illustrate initial deformation, primary creep and secondary creep of a material subjected to a constant load over time. Students can observe a phenomenon over a few days that often takes years to complete. Students can compute the steady state creep rate and gain an appreciation for the relative time required for primary and secondary creep. This demonstration should take a 20 minutes during a single class, but be monitored and updated over a 3 day period..

Engineering Principle: Creep is defined as the permanent deformation over time of a material subjected to a constant load or stress. For metals, it occurs at higher temperatures, usually greater than 40% of the melting point, and can take years to occur. It is therefore difficult to physically illustrate this concept to students. Fortunately, many polymers experience creep at room temperature and at stresses far below the yield stress of the material. Thus it is possible to create a quick, inexpensive and rudimentary demonstration of creep behavior in the classroom using plastic tubing with a suspended weight. Creep occurs in stages as indicated by the Figure 1.



When a load is applied to an object, there is an instantaneous initial deformation that can be computed using basic principals of stress and strain. This first stage of creep is known as *primary* creep where the slope of the curve is decreasing and the material is experiencing strain hardening. The curve levels off to a constant slope during the *secondary* stage of creep. This is the longest stage of creep and the material is achieving a balance between strain hardening and recovery of its deformation capability. The slope of the line during this period is the *steady state creep rate*. The final stage of creep is the tertiary stage and ultimately leads to rupture of the material. The slope of the curve increases as the microstructure of the material changes, cracks form, and the material ruptures.

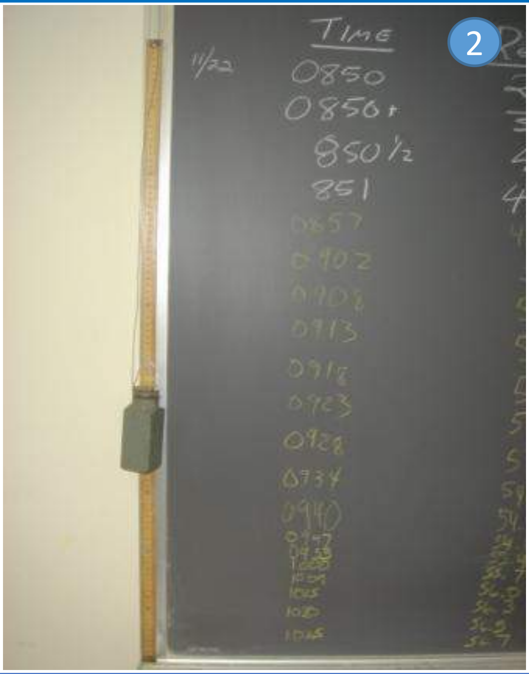
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Surgical Tubing	3 to 8 feet	$5-10	Any small diameter piece of tubing will work. You will want a piece that is long enough for the students to observe the deformations yet short enough to fit in your classroom. Longer pieces of tubing will produce larger deformations.
Weight	1	$5	The weight should be large enough to cause a substantial initial deformation, roughly 20-40% rupture strain. (20-40% of rupture strain if using tubing. If using another material, 20-50% of e_y might be appropriate). If the weight is too small, the creep curve will take a long time to develop. If it is too big, the creep will either be unrealistically accelerated or produce an early rupture.
Hook	1	$5	Attach the hook to either the ceiling or an upper portion of the wall.
Yardstick	1	$3	Attach the yardstick to the wall, next to the hanging weight. Use either a screw or tape. If tape is used, provide a sufficient quantity that a minor disturbance will not cause the yardstick to move

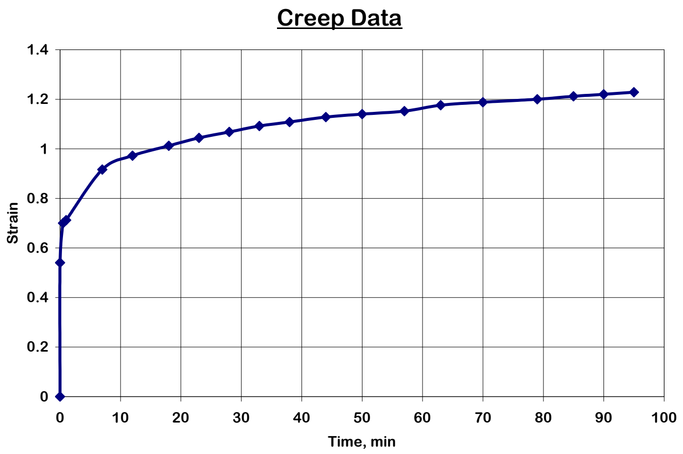
APPLICATION

<u>Before Class</u>: Mount a hook in the classroom from which to hang a weight suspended from a long piece of surgical tubing. Affix the yardstick to the wall next to where the weight will hang. Tie the surgical tubing to the weight, but do not hang it yet. This should take 10-15 minutes.

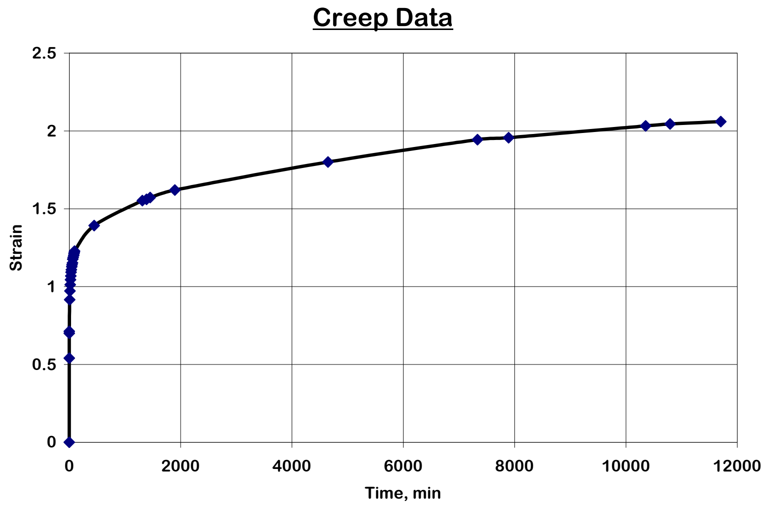
<u>In Class</u>: Attach the surgical tubing to the hook and mark the location of the weight in the undeformed position on the yardstick. You will have to suspend the weight in your hand to make this mark. Gently release the weight, allow the surgical tubing to deform and record the difference between the initial mark and its current location on the yardstick. Record the data on the blackboard. Have a student take a reading every minute for the first five minutes. Record the time and the reading on the yardstick on the blackboard. Continue taking readings every five minutes for the remainder of the class period. 2



Prepare a spreadsheet in advance and enter the data into the spreadsheet. Divide the deformation by the initial length of the surgical tubing to obtain the strain. Convert the recorded clock times to a standard unit of time such as hours or minutes. At the end of the class period, an initial creep curve can be posted on the board. Data from an actual class experiment after 100 minutes is shown below.



Continue taking readings over several days at convenient times. They do not have to be taken often. At the beginning of class, show the updated creep curve. For the experiment shown below, the data was collected over nine days.
It may not be productive to continue the experiment any longer. The learning points have been made and it is unlikely that anyone will be around to capture the data for tertiary creep. It will happen quickly and may occur during the middle of the night. You will probably have moved on to another topic, so quit while you are ahead, unless the students are interested enough to continue the experiment to rupture.



<u>Additional Application</u>: Incorporate the data generated into a homework problem. Have the students estimate the steady-state creep rate and use it to solve a problem. Ask the students to identify the regions of primary creep and secondary creep. Have them comment on the amount of time the tubing spent in each stage. When determining creep life, is it reasonable to neglect primary creep? Discuss the difference in short-life creep applications where the time to rupture is the most relevant engineering parameter and long-life creep applications where the steady-state creep rate is the more applicable. Discuss how actual creep rupture tests are conducted in the laboratory and compare it to the simple experiment just conducted.

MECHANICS

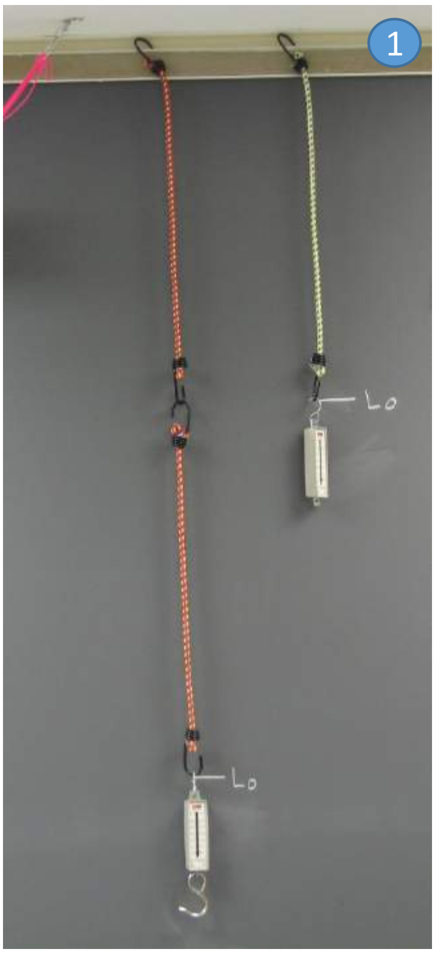
AXIAL STRAIN #1

MECHANICS

Keywords: Axial, Deformation, Strain, Stress

Submitted by: John Richards

Model Description: This is a simple demonstration of the basic principles underlying the behavior of materials subjected to an axial load. The demonstration can also be used to show the usefulness of stress-strain curves versus load-deformation curves. This demonstration should take 10 minutes.



Engineering Principle: The basic definitions for deformation and strain

$$\delta = L_f - L_o$$

$$\varepsilon = \frac{\delta}{L_o}$$

where the axial (longitudinal) deformation is equal to the final length minus the initial length. The longitudinal strain is equal to the axial deformation divided by the initial length. Further, according to Hooke's Law, the strain will follow the stress, so observed deformations are indicators of the magnitude of stress.

REQUIRED ITEMS

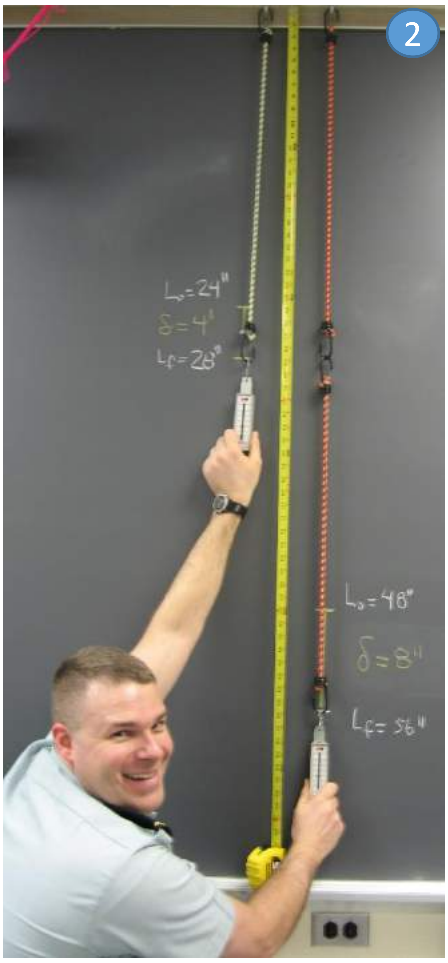
Item	Qty	Cost and Build Time	Description/Details
Bungee Cords	3	\$10	Make sure all three cords are the same length and width. Attach two cords together to make one long one.
Load Meter	2	\$20 each	A method of measuring the load to make sure that the same load is applied to each section of cord is required.
Tape Measure	1	\$10	It needs to be long enough to measure the total length when stretched.

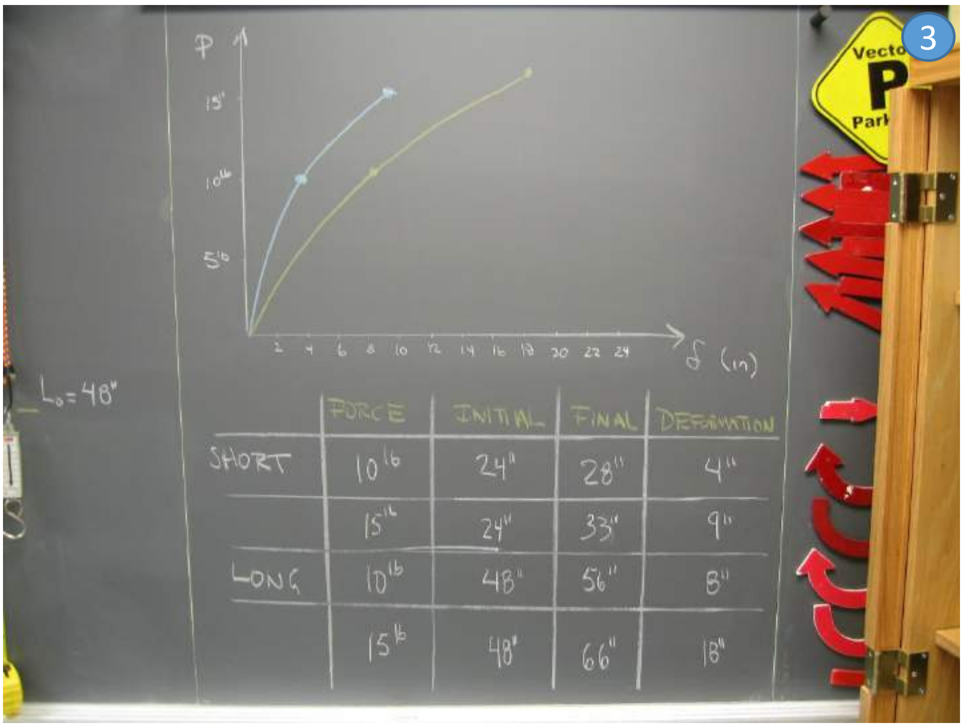
APPLICATION

Before Class: Prepare a method for hanging the bungee cords. Hooks above the blackboard are ideal, or hang them from a low ceiling or use another method.

In Class: Hang the two different lengths of cords. 1 Get an initial length of the cords (Put the load meters on just to put a little load on them to straighten them out). Apply an equal load to each of the cords and measure the final length. This allows you to calculate the deformation. 2 Apply a greater load (doubling the initial load works well) and again measure the final length and calculate the deformation. Then plot the load deformation curve. 3

Observations: As is shown by the load-deformation curves, for every different length of material, you will need a separate curve. Then discuss how different thicknesses will also affect the results. This leads to the conclusion that load-deformation curves are very inefficient and cumbersome, hence the power of the stress-strain curve, which normalizes the load-deformation data for any size of the same material.





Additional Application: You can also drive home the point that load-deformation curves are inefficient by showing differences in deformation between bungee cords of the same length, but different thicknesses.

FOAM BEAM

MECHANICS

Keywords: Beam, Bending, Compression, Deformation, Plane Sections, Tension, Torsion

Submitted by: Ronald Welch

Model Description: This simple demonstration depicts how moments (and forces) result in bending of a beam and how the deformation is related to the assumptions associated with elastic beam behavior. A foam beam with vertical lines (black lines) and a horizontal line drawn along the neutral axis (red line) for a rectangular beam is used to demonstrate bending behavior. The orientation of the lines during bending provides a simple physical representation of flexural theory. 1 This demonstration should take 3-5 minutes.

Engineering Principle: The foam beam can be used to show many concepts surrounding flexural behavior, but the easiest and possibly most difficult to visualize without a physical model is plane sections remain plane. Additionally, many students will be able to see that a positive moment (based on the established sign convention) results in the beam that looks like a smile in which the top fibers are in compression and the bottom fibers are in tension while the fibers at some point in between are not experiencing tension or compression, i.e., the neutral axis. 2

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Foam Beam	1	$2-7 depending on size; 25 minutes	The beam can be any reasonable size. This example used a 23.5 inch long beam with a 4"x4" square cross-section in the first two images. A 2”x2”x12” foam beam works just as well. The material is basic furniture foam.
Markers	2 colors	$3 for the pair	These are used to draw lines on the beam. One color (**red**) is used for a horizontal line down the whole length of the beam in the middle (neutral surface). Ten to fifteen vertical lines are drawn towards the middle of the beam, spaced about an inch apart, with the other color (**black**).

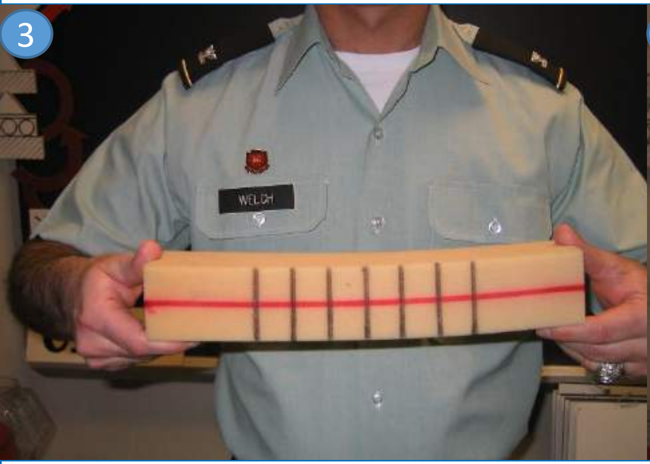
APPLICATION

Before Class: Prepare the beam with the lines drawn on it.

In Class: Show the class the beam 3 and ask what they think will happen when you apply a moment to it. More directed questions could be: Which lines will change shape and/or orientation? What will happen to the distance between the black lines?

Then apply a moment using a hand at each end of the beam so that the beam begins to bend into a slight smile and ask what just happened. 4 Point out the deformation of the red line—it is now curved—but that it did not change in length while the top surface and the bottom surface did change length. This can be seen by observing the change in the space between the black lines. At the top of the beam, the lines moved closer together (compression), while at the bottom of the beam the lines moved farther apart (tension). The distance between black lines along the red line is still the same. But also point out that the black lines themselves did not deform - they are still straight. Plane sections remain plane during elastic bending. The change in the spacing of the lines shows that the top of the beam is in compression, and the bottom is in tension.
Note: The size of the rectangular beams does not matter. A 2 inch square foam beam can also be used.

3



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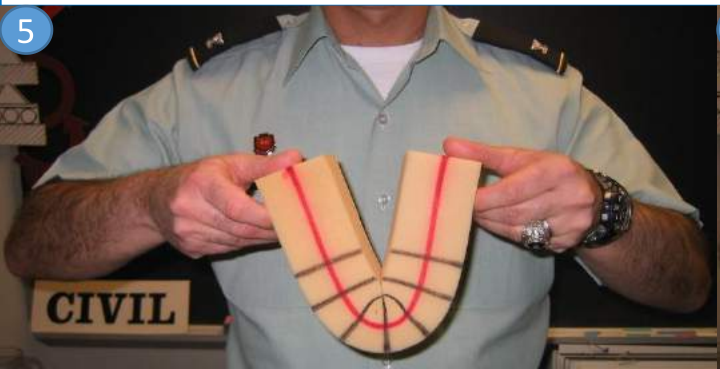
Additional Application: There is usually a lot of confusion as to when the assumptions of flexural behavior are no longer valid. The foam beam can be used to provide some insight into the fact that flexural theory is only valid when the assumptions are valid. Bending a beam to the point that the vertical lines are no longer straight visually demonstrates that the assumptions are no longer valid when the beam experiences large deflections and plane sections are no longer plane. The students can see this theory under the large deformations the beam is experiencing and the professor can further enforce that the assumptions (and associated flexural equations) are only valid for elastic conditions. 5
When discussing torsion, torsional loads on square shapes causes warping and is very difficult to determine how much of the material is resisting the applied twisting moments. 6

5



6

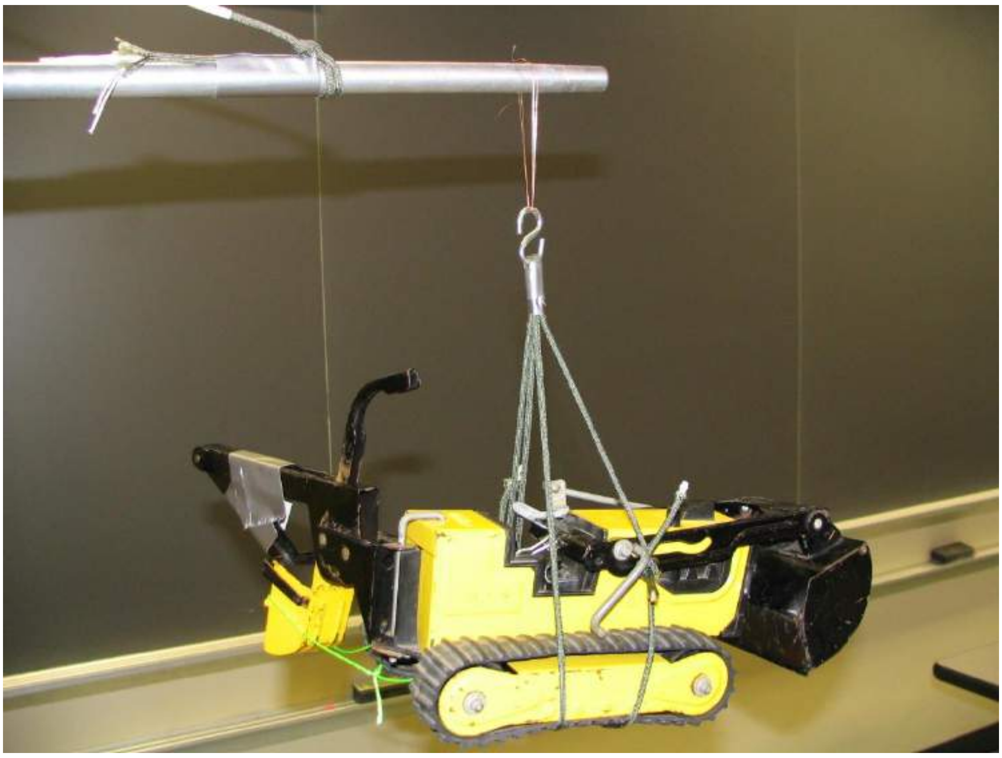
DESIGN OF AXIAL MEMBERS

MECHANICS

Keywords: Axial Load, Factor of Safety, Stress

Submitted by: Matt Morris, Tom Messervey, and Led Klosky

Model Description: This is a simple demonstration to introduce the basic principles of experimentation, analysis, and design in reference to axially loaded members. Copper wire is used to lift an object of known weight. In order to determine the minimum number of copper wire strands required to lift the load, students perform experiments, analysis, and design calculations. The discussions in class inherently lead to an understanding of the practicality of experimentation, the need for a factor of safety in actual design, and actual-versus-allowable stress. This demonstration should take 15-20 minutes.



Engineering Principle:

The basic equations for axially loaded members:

$$\sigma_{actual} \leq \sigma_{allowable}$$

$$\text{where } \sigma_{actual} = \frac{P}{A}$$

$$\text{and } \sigma_{allowable} = \frac{\sigma_{ultimate}}{F.S.}$$

$$\text{therefore, } \frac{P}{A} \leq \frac{\sigma_{ultimate}}{F.S.}$$

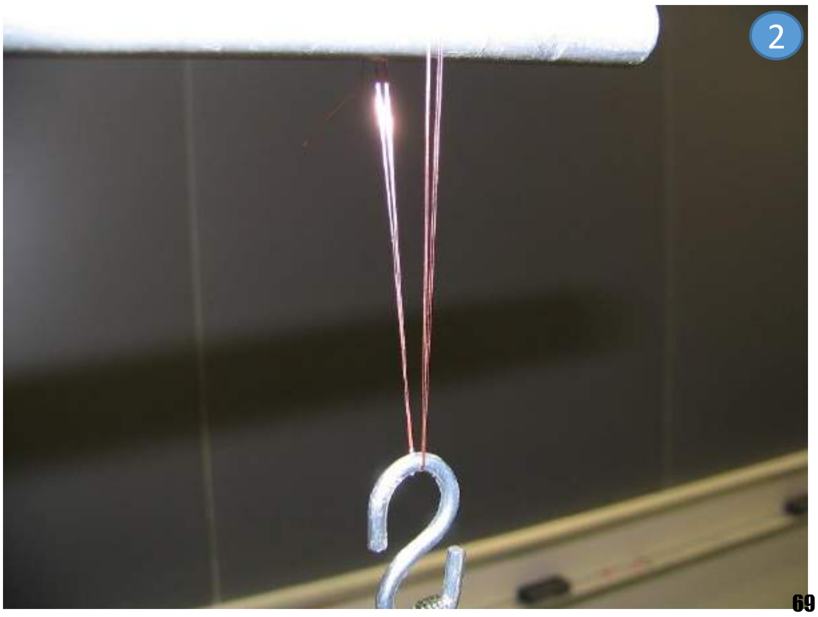
where the actual normal stress imposed on the member must be lower than the allowable normal stress. The actual normal stress in a member is the axial load over the cross sectional area. The allowable normal stress in this case is the ultimate strength of the material divided by a factor of safety. Therefore, if the material properties, expected load, and factor of safety are all known, the required cross sectional area can be determined and the member can be sized to carry the load.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Copper Wire	Lots	$20; 20 minutes	Any wire will work, but the ultimate strength and diameter must be known before class. Copper wire is preferred as it ruptures without having to use much weight. The wire used in this example is annealed copper wire with a diameter of 0.006 in., a yield strength of 8,000 psi, and an ultimate strength of 33,000 psi.
Load	1	$10; 15 minutes	Use anything as a load. This demo uses a load with a total of 5 lbs.
Scale	1	$10	Any scale to determine the weight of the object.
Crane	1	$15; 20 minutes	The easiest objects to use as your crane are yard sticks or broom handles. Depending on the level of drama you want in the classroom, you can enhance your crane by using more complicated setups as seen in the photos below.

APPLICATION

Before Class: Prepare several loops of copper wire with various numbers of strands. 1 Prepare the load you are going to lift by ensuring that it has something (like a hook) 2 to attach the loops of copper wire. It is important that you make a couple of trial runs before class to ensure that secondary effects (like kinking of the wire) are minimized and don't drive the behavior.



__In Class__: Challenge the class by asking them to determine how many strands of copper wire are required to lift the given load. Weigh the load in front of the class and record it on the board. (In this example, the load is 5 lbs.)

Conduct the experiment portion of the lesson. Ask the students if one loop (two strands) of copper wire will carry the load. Try to lift the load with two strands of copper wire. Given the example 5 lb load and copper material properties described above, the copper fails with two strands. Ask the class what they suggest. Inherently the students will suggest adding more wire. Try to lift the load with your pre-made loop of four strands. In our example the wire deforms more slowly than before, but still ruptures. Discuss with the students that experimentation is great in the classroom and a lab, but is not feasible on a real job site. This will lead into the need for design.

Conduct the design portion of the lesson. Using the equations described above, rearrange and solve for the minimum cross sectional area required to lift the load.

$$A \geq \frac{P \times F.S.}{\sigma_{ultimate}}$$

In our example:
P = 5 lbs.
F.S. = 1 since we merely want to lift the load
$\sigma_{ultimate}$ = 33,000 psi. Obtained from a material properties table for annealed copper

Solving the equation:
A ≥ 0.000152 in^2
Dividing this value by the cross sectional area of one wire with diameter of 0.006 inches will yield the minimum number of wires required to carry the load:

$$\#\ of\ strands = \frac{Area_{min}}{Area_{strand}} = \frac{0.000152\ in^2}{\pi \times \left(\frac{0.006\ in}{2}\right)^2} = 5.38$$

Therefore, based on __design__, we will use 6 strands to ensure that the wire does not break. Conduct another experiment using 6 strands. You will be able to lift the load. Now ask the class how confident they are with 6 strands. Tell them in real life there might be some circumstances that require more strands; it might be a windy day, the crane operator might not be smooth on the controls, the load may be slightly higher than we estimated, etc. At this point shake the crane rig slightly and it should fail.

Now is the best time to introduce the importance of factor of safety and how risk comes into play. Perform an __analysis__ using 8 strands and determine the factor of safety you are building into the design. Rearranging the equation and solving for F.S.:

$$F.S. = \frac{\sigma_{ultimate} \times Area}{P} = \frac{33{,}000\ psi \times \left(\pi \times \left(\frac{0.006\ in}{2}\right)^2\right) * 8\ wires}{5\ lbs.} = 1.5$$

<u>Additional Application</u>: As you can see from the video, you can use toy tanks, cars, or anything as a load to grab the students' attention. Your crane setup can be extravagant; in the video we have a system of pulleys and we've also used toy cranes. During the experiment portion of the lesson students will start to enjoy the lifting of the tank, and the subsequent breaking of copper wires. Tell the students when they start testing that they are responsible if anything breaks! This will bring home the point that if you are to lower your risk, you need to increase your factor of safety. However, increasing your factor of safety will increase your cost too. With some basic role-playing (the instructor is the contractor and the students are the engineers) you can get the students to realize that the number of wires chosen can impact a career!

ELASTIC VS PLASTIC DEFORMATION

MECHANICS

Keywords: Axial, Deformation, Elastic, Plastic, Strain, Stress

Submitted by: John Richards

Model Description: This is a simple demonstration of the basic principles underlying the elastic and plastic behavior of materials subjected to an axial load. The demonstration can also be used to show the highlight the elastic and plastic portions of stress-strain curves. This demonstration should take 8-10 minutes.

Engineering Principle: The basic definitions for stress, deformation, and strain

$$\sigma = \frac{P}{A} \text{ (stress)}$$

$$\delta = L_f - L_o \text{ (deformation)}$$

$$\varepsilon = \frac{\delta}{L_o} \text{ (strain)}$$

where the stress is force over area, axial (longitudinal) deformation is equal to the final length minus the initial length. The longitudinal strain is equal to the axial deformation divide by the initial length. Further, according to Hooke's Law, a stress-strain curve for each material can be developed showing elastic and plastic behavior.

Hooke's Law

$$E = \frac{\sigma}{\varepsilon}$$

where the Modulus of Elasticity (Young's Modulus) is equal to the normal stress divided by the longitudinal strain. Further, in the Elastic Region of the stress-strain curve, a material will return to its original shape while in the Plastic Region permanent deformation is induced. The material finally ruptures and breaks.

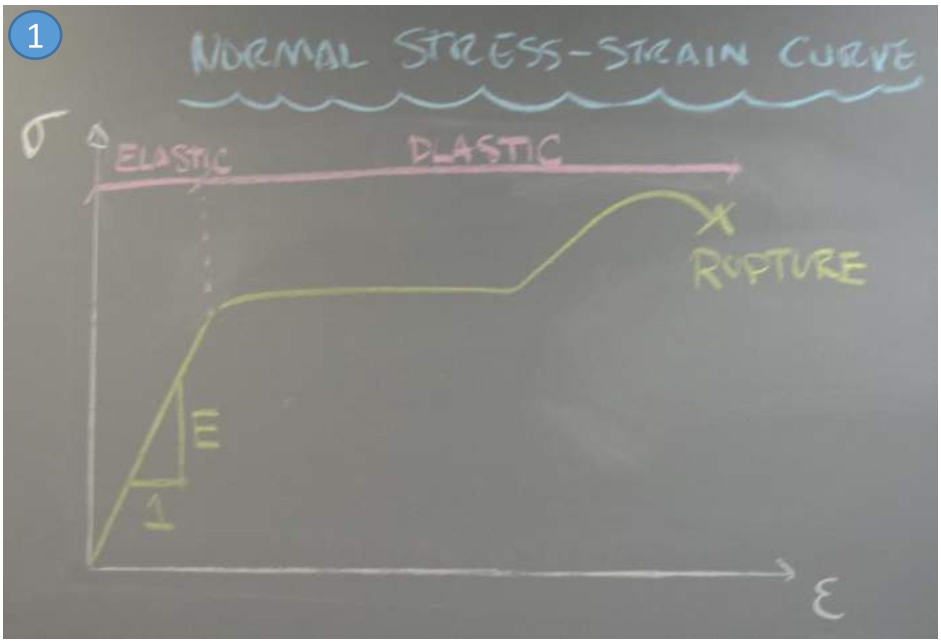
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Twizzlers	Varies	$5	Each student will need two Twizzlers, one control and one experimental.

APPLICATION

Before Class: Purchase enough Twizzlers so that each student and the instructor will have two. It also helps to open the package before hand to speed up the process.

In Class: During the lesson, the stress-strain curve is drawn and the various regions on the curve are identified (Elastic, Yielding, Inelastic/Plastic, and Fracture). 1 Then bring out the Twizzlers to allow the students to make real-world observations about these various material behaviors.



Each student will have one Twizzler as a control and the other will be used for the experiment. First, have the students pull on the experimental Twizzler with a small amount of force and notice how it will go back to its original length as compared to the control Twizzler (the Elastic Region). Next, have the students pull on the Twizzler more, just enough to induce permanent deformation so that it remains longer than the reference Twizzler, but not enough to break it. 2 Plastic behavior! Finally, have them pull on the Twizzler with enough force to cause it to rupture! 3

Observations: Point out the difference between deformation/strain in the elastic region (the Twizzler returns to its original length every time) and plastic region (permanent deformation).

After using the Twizzlers for the demo, destroy the evidence by eating the training aids!

RUBBER SHAPES

MECHANICS

Keywords: Buckling, Compression, Cross-Section, Load Conditions, Tension, Torsion

Submitted by: Ronald Welch

Model Description: These physical models easily and quickly demonstrate the behavior of varying cross-sectional shapes to varying loading conditions. When the instructor passes the rubber shapes around during class, students personally experience the associated behavior and quickly catalog for themselves when shapes are best used. Applying vertical, horizontal, and circumferential lines along the length allow for physical representation of the assumptions associated with each type of loading and shape that are not always intuitively obvious to our students. This demonstration should take 20-25 minutes.

Engineering Principle: The shape of structural members affects their behavior during loading. Some shapes have more strength and stability versus other shapes when identical forces are applied. Flexural, axial, torsional, and buckling behaviors and assumptions can be demonstrated and experienced using these rubber shapes. Additionally, the importance of a shapes area moment of inertia (a physical property) can be highlighted.

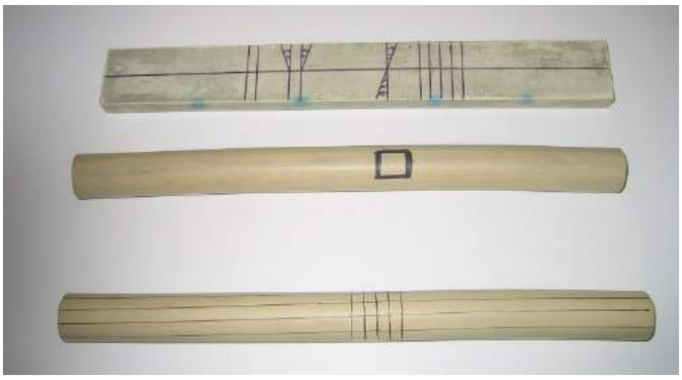
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Rubber Cylinders	2	$8*	These are about a foot long and an inch in diameter. To demonstrate torsional behavior of cylindrical members, draw 10-12 lines lengthwise and evenly spaced around the circumference of the cylinder. These lines should form squares. On the other cylinder, you can draw one large square.
Rubber Rectangular Members	2	$8*	Dimensions are 12” long x 1½” wide x ½” thick. Various patterns can be drawn on the largest side of one of the members to demonstrate flexural behavior. Generally vertical and horizontal lines along the length are drawn.
Rubber Wide-Flange Beams	2	$12*	Dimensions are 18” long x 2” tall x 1½” wide (flange) and ⅛” thick (flange and web).
Rubber Angles	2	$10*	Dimensions are 18” long x 1½” x 1½” (⅛” thick) - an equal leg angle. When two angles are clipped together, we can demonstrate the need for intermediate connections along the length in order to increase the strength (due to buckling).
Binder Clips	3		These are used to hold the two angles together.

*Any rubber producing company can probably extrude these rubber shapes. However, the largest initial cost is the production of the dyes. These costs do not include the price of the production dye.

APPLICATION

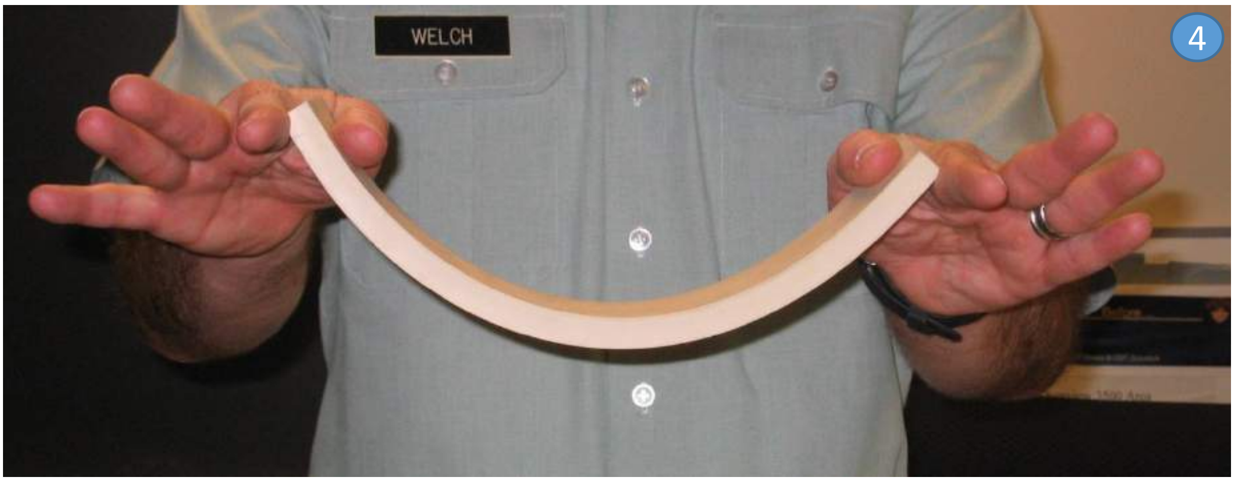
Before Class: Draw the patterns on the shapes that require it based on the lesson at hand. Be sure you have all of the shapes and clips necessary for each demonstration.

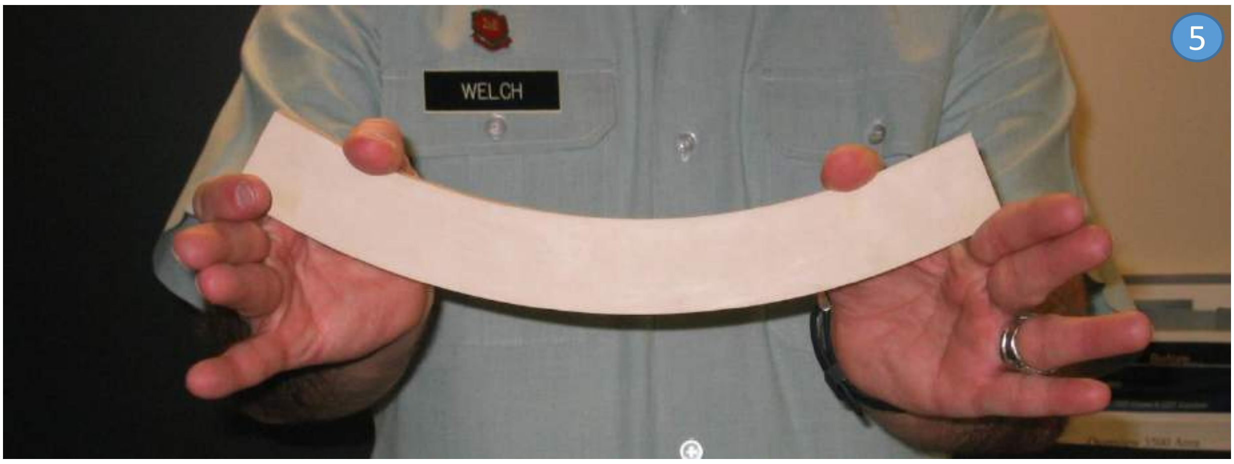


In Class: Depending on the lesson, bring out the rubber shapes of choice for everyone to see. If the lesson is on torsion, maybe both the rectangular and cylindrical shapes are used. Ask the students: how the different shapes will behave when applying a torsional moment? First, take the rectangular beam and twist is and see that it warps. Twist the cylinder and notice that it does not warp and is possibly a more efficient shape for members that will experience only axial loads and/or torsional moments. Start with the rod with only a single square drawn on it. Ask the students: what will happen to the square if the rod is twisted? Twist the cylinder with a single square drawn on it. Show the students how the square turns into a rhombus. 1 The area of the square does not get larger, but the square just changes shape to a rhombus. This behavior opens the discussion on the pure shear behavior of cylindrical shapes and can be demonstrated numerous times during the development of the shear strain/stress theory.

The discussion can be further enhanced with the twisting of the other rod with the series of lines along the length and around the circumference. 2 Highlight that the longitudinal lines twist like a candy cane while the vertical lines do not distort – stay vertical. 3 The squares still deform to form a rhombus where the square changes shape, but not size. This demonstration depicts key highlights of pure shear deformation. Additionally, highlight how the overall shape of the rod does not change when twisted in comparison to the rectangular beam. The rectangular beam can be twisted to show warping.

In Class: During lessons on flexure, use the unmarked rectangular beam. Ask the class which way it would hold more load? Apply a moment to the beam when it resists with the smallest area moment of inertia 4 and observe how easy it is to bend and how much it bends. Rotate the beam and apply a moment when it has the largest area moment of inertia 5 and note how much more difficult it is to bend it and how little it bends. Most students can make this connection to their experiences of using left over 2"x4" wood members to build a fort, a tree house or a foot bridge over a neighborhood stream.

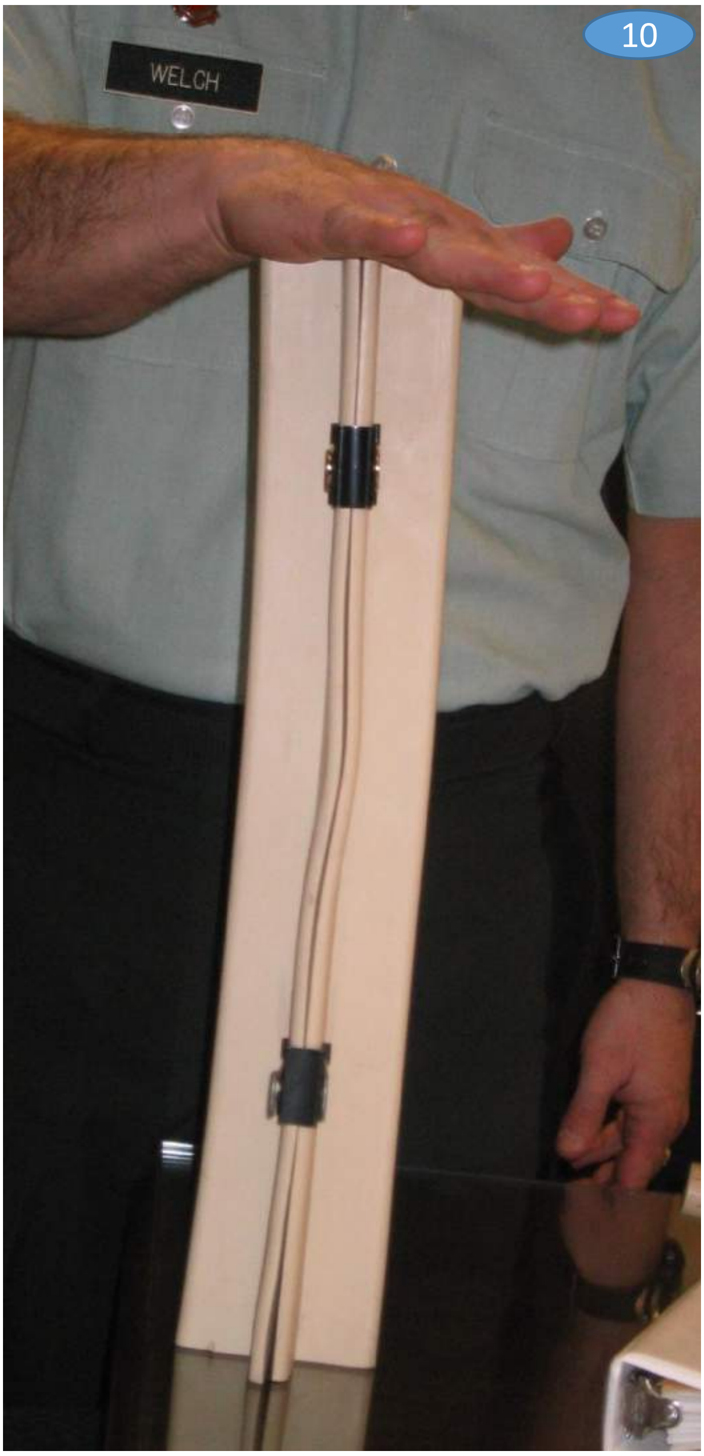




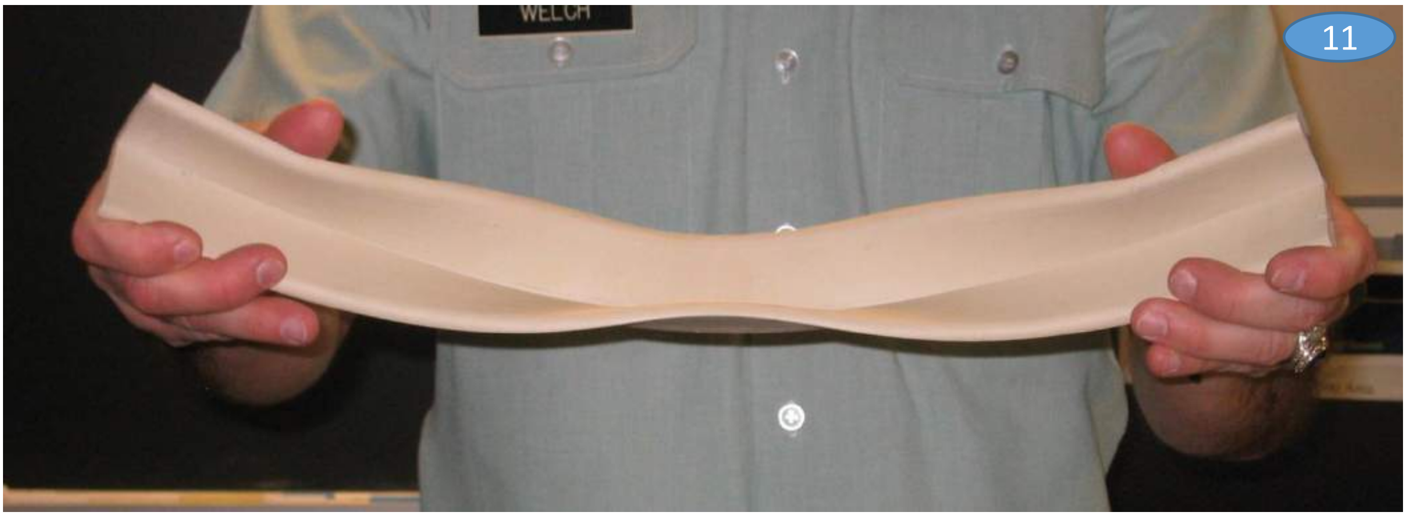
Just as with the foam beam example, vertical and horizontal lines drawn along the length demonstrate the assumptions associated with flexural behavior. Point out the deformation of the horizontal lines—they are now curved—but the central horizontal line did not change in length while the top and bottom lines did change length. This can also be seen by observing the change in the space between the vertical lines. At the top of the beam, the lines moved closer together (compression), while at the bottom of the beam the lines moved farther apart (tension). You can also point out that the spacing between black lines does not change along the neutral axis. But also point out that the vertical lines themselves did not deform - they are still straight, unless we load the beam to cause large deformations... This is similar to what can be shown using the foam beams. 6

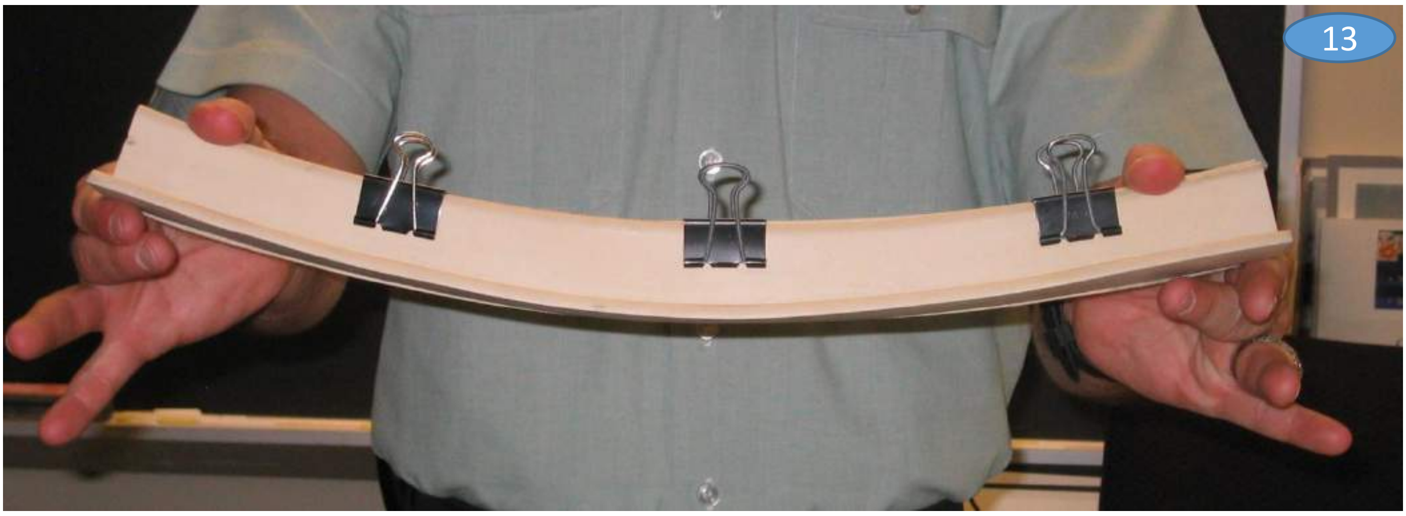
In Class: The wide-flange shaped beam can demonstrate the additional stiffness when the area moment of inertia is increased by moving more of the cross-sectional areas further from the shapes neutral surface/axis. The shape is very useful in steel design when desiring to demonstrate lateral-torsional buckling of wide-flange members (if not discussed in Mechanics of Materials). When moments are applied to either end of the long beam, it experiences lateral-torsional buckling and buckles laterally. But as the length of the beam between load points is decreased, greater moments are required to cause lateral-torsional buckling. 7 So the importance of intermediate lateral support is directly shown and physically demonstrated/emphasized for the students. Additionally, wide-flange members are used as columns. Again, with no intermediate supports along the length, a longitudinal load will result in the column bending/bucking about the weak axis or the axis with the smaller area moment of inertia. Point out the fact that when a wide-flange member is used as a beam or column for its greater flexural strength along one of the axis, the weaker axis generally requires some type of lateral support. 8

In Class: The final rubber shape member is the angle. When an axial compressive force is applied to a single member, it buckles easily. 9 So usually we see the use of this shape for tension bracing members. Ask the class: what they think would be best to modification to address the issue of buckling? Hopefully the previous lessons will have highlighted the need for additional area moment of inertia. Use a second angle and clip them together using the binder clips – one at each end. Apply the same force to the new composite member in the same method as before and demonstrate that the column doesn't buckle as easily, but it might still buckle some at the center. Add another clip in the center, and reapply the load to demonstrate that even more load is required to buckle the double angle configuration (this step might not be required if not applying to large of a load and if you are going to demonstrate the next step below in the same class). 10 Again, the importance of area moment of inertia is highlighted, but also the importance of connection of multiple members to ensure that the individual members must be made to act as one to gain the desired advantage – increased (buckling) strength.



In Class: The same general behavior can be demonstrated while loading an angle in flexure. Once again, it buckles while demonstrating lateral-torsional buckling at mid-span. 11 Ask the class again what should be done. It is now clear that additional area moment of inertia is required (another angle) and that the angles must be connected. Once the class gives the answer, clip the two angles together with two clips just as before. 12 Apply the same moment to the ends of the beam so that it buckles in the middle. Once again, ask the class what should be done. Attach a third clip to the middle of the beam and show that this beam is much stiffer/stronger than before. 13





Additional Application: These shapes are not only useful in a basic Statics class to show how loads are applied, but especially useful in a Mechanics of Materials class. However, any class where the behavior of the member is important (steel design, concrete, design, structural pieces in mechanical design, i.e. automotive and aircraft frames), these rubber shapes are an efficient method to review and/or reinforcement of past discussions of member behavior.

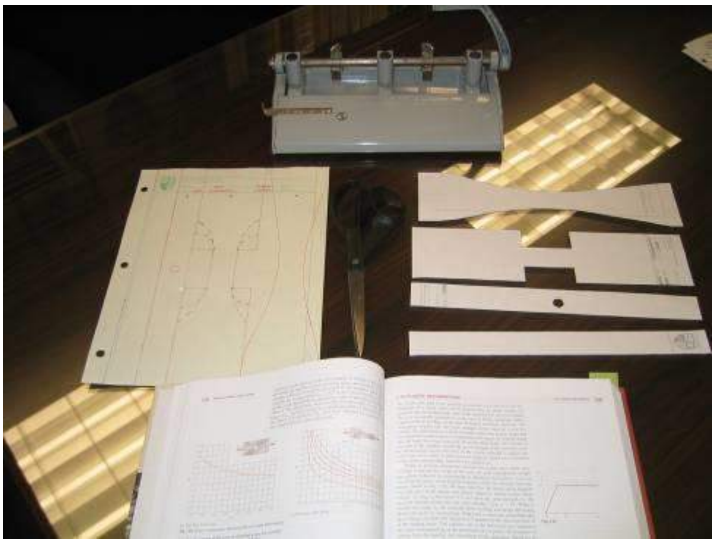
PAPER STRESS CONCENTRATIONS

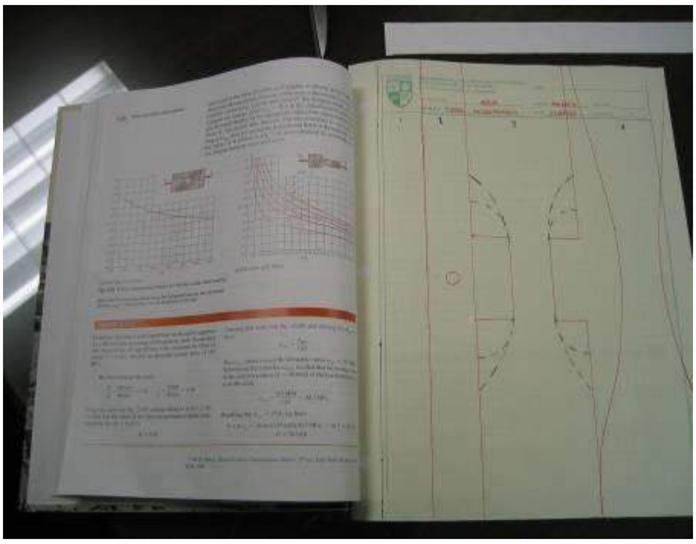
MECHANICS

Keywords: Discontinuity, Point Load, Stress Concentrations

Submitted by: Ronald Welch

Model Description: This is a simple demonstration of the basic principles and behavior underlying stress concentrations. Stresses at points of load application can be much larger than the average stress in a member. The same is true when a member contains a discontinuity. Paper members with the same mid-span width are used to demonstrate the stress concentrations that can occur at load points as well as at discontinuities: holes and fillets. This demonstration should take 8-10 minutes.





Engineering Principle: The stress concentration factor (K) is defined for a particular cross-section as

$$K = \frac{\sigma_{max}}{\sigma_{avg}}$$

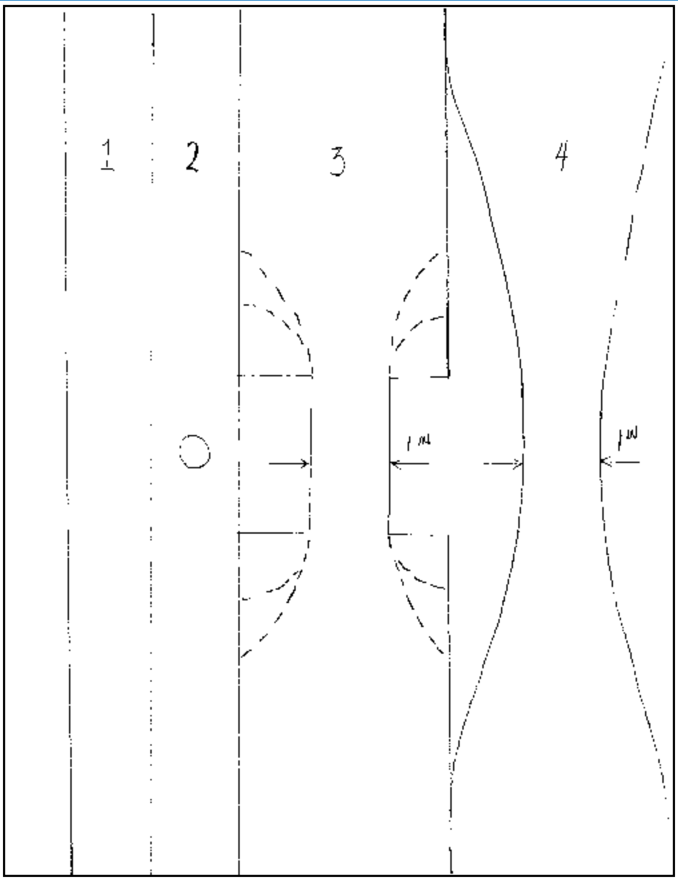
the maximum stress over the average stress. The maximum stress typically occurs near a discontinuity. The experimental results obtained for K are independent of the size of the member and the material used; they depend only upon the ratios of the geometric parameters involved (i.e., diameter of the circle, radius of fillet, or remaining width of cross-section).

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Sheet of paper members	2 sheets per student	3 minutes per sheet	Cut out the shapes. Two sheets/shapes per student. There are four shapes. Shape 3 has three (multiple) different configurations. Get some help if you have a big class.
Scissors	1	$8	It important not to create stress concentrations when cutting out the members (i.e., do not create notches when cutting out the shapes), especially the third member with the square corners.
Single hole punch	1	$5	Used to put the hole in Member 2.

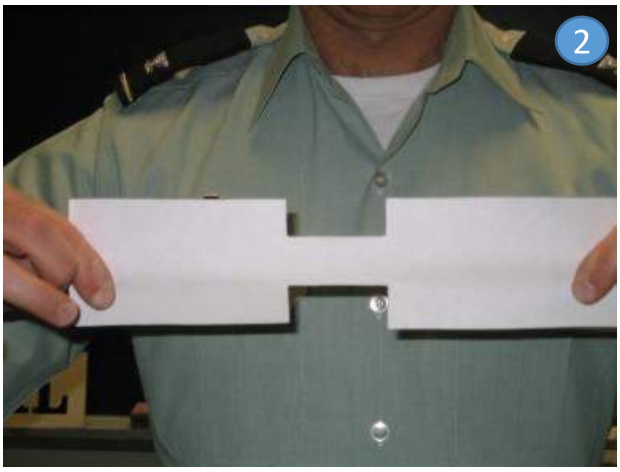
APPLICATION

Before Class: Cut out the members so that each student has at least one of each of the four paper member configurations. 1 Note that the cross section at the middle of each member is the same (in this case 1 inch). Member 3 has three configurations – no fillet, a circular fillet and a larger/possible non-circular fillet. You decide if they have one of each – the reason for two sheets of members - per student. Also many students will place impact loads on the members, so they will need replacement members when this occurs.



1

In Class: Have the students make a prediction as to which member will break with the least to most load. After the presentation of the theory, calculate the max stress each member will experience based on an assumed applied load. The students then reorder their predictions and statically load their specimens 1 thru 4 (specimen 3a (with no fillet, just a notch cut), specimen 3b with one of the two fillets) by only using their thumb and index finger. We could use a clamp and a spring load for accuracy, but that is not really necessary. After hand loading the first member, some students apply a pinching action at their load points that causes a stress concentration and pre-mature failure at the finger locations. Others will apply the load as an impact load. Each loading situation provides key discussion points for the effect of the load on the experiment (and the reason for having more than one member type per student). Emphasize the need to not create a stress concentration at the finger point. It is important that each student has a Member 3 that has no fillet, just the notched out section. 2



2

In Class:

Observations: Some students will not be able to break Members 1 and 4 at the center without an impact load (moving fingers towards each other, then applying a tension load rapidly) or at the load point with a pinching effect. The students should observe that a gradual change in shape will allow for a smaller stress concentration factor - less of a stress concentration effect (i.e., the stress concentration factor is reduced as the radius of curvature of the fillet is increased). They should also see that no fillet is a very dangerous situation and creates a very large stress concentration at the corner.

Additional Application: Some students will not be able to break Members 1 and 4 at the center without an impact load or at the load point with a pinching effect. Highlight the strength that some materials possess in tension when we see very little strength in compression. This spurs a deeper discussion back into the reason we are studying mechanics of materials or the strengths and behaviors of materials. The proper selection of the proper material leads to efficiency and cost effectiveness. It is also humbling to see some of the stronger students not be able to break a simple piece of paper…

SHEAR DEMONSTRATOR

MECHANICS

Keywords: Rectangular Members, Shear

Submitted by: Ronald Welch

Model Description: These demonstrations show the effects of shear within rectangular members. This demonstration should take 10-15 minutes.

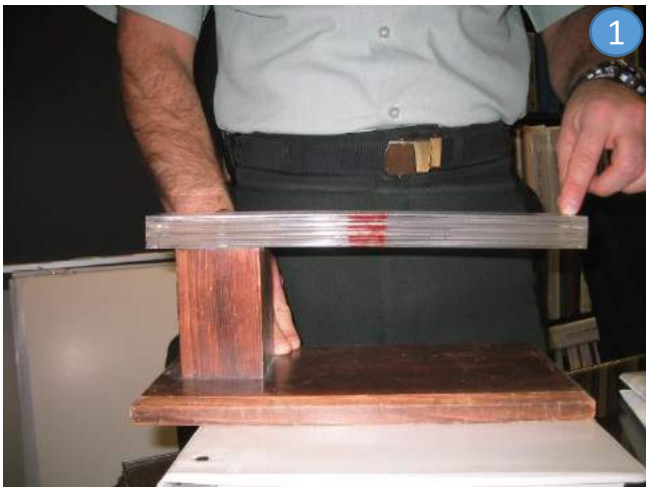
Engineering Principle: When a load perpendicular to the longitudinal axis is applied to a beam, the force is transferred through the beam through shear. With the help of these two demonstrations, the students will better understand how a load applied perpendicular to the longitudinal axis is transferred to the reactions of the beam. The goal is to demonstrate how the force is transferred through horizontal shear and to establish a physical representation to the development of the theory on shear in rectangular beams. Additionally, these physical models highlight how members fail if caused by shear.

REQUIRED ITEMS

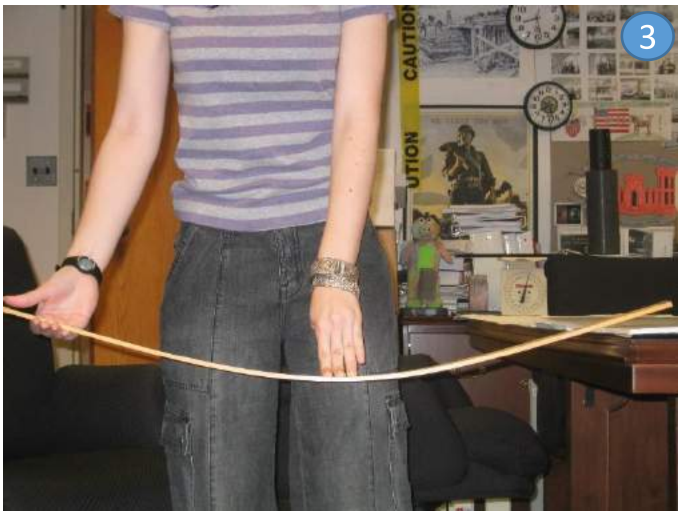
Item	Qty	Cost and Build Time	Description/Details
Plastic Rectangles	12	\$40; 45 minutes	These are clear pieces of plastic 12" long x 2" wide x ⅛" thick. Eight of them are stacked on each other and connected at one end by a screw driven through them into a piece of wood. The other four are used for the other prop. These have three holes in them: two oblong holes about 3" from each end, 1" long and ½" wide, and a third hole in the middle of the member, ½" diameter.
Red Marker	1	\$1	This is used to draw a square on the member made of the 8 plastic rectangles. The rectangle is right in the middle of the member and drawn on the edge of the members.
Nut and Bolt	1	\$2	5½” bolt with a matching nut to attach the two pieces of wood to the plastic.
Base	1	\$20; 25 minutes	The base is made of two pieces of wood—the top piece 3¾” x 2½” x 2½” and the bottom piece 12” x 6” x ¾”. The two are connected with a screw and a nut so that the top piece is on one edge of the bottom piece to establish the condition that the connection of the plastic pieces results in a cantilever beam.
Yardstick	1	\$4	The ruler is used as a sort of introduction to shear. Applying a load to it brings around the question of how a load applied to the middle of a beam gets to the ends of the beam.

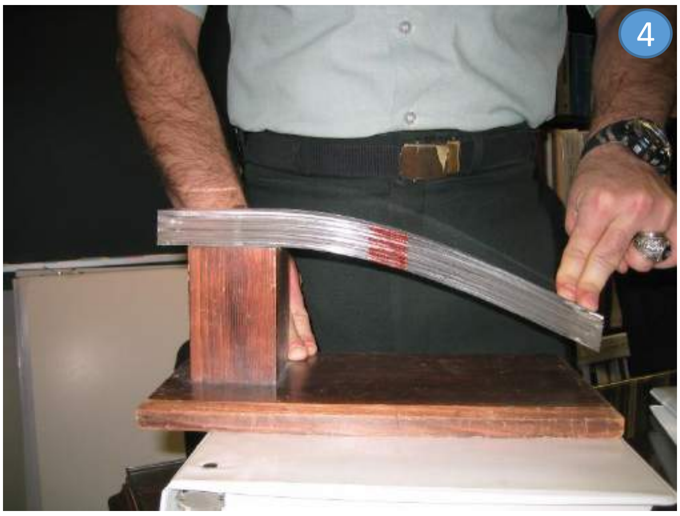
APPLICATION

Before Class: Prepare the two props and test them to be sure that you can create the proper effect. 1 2



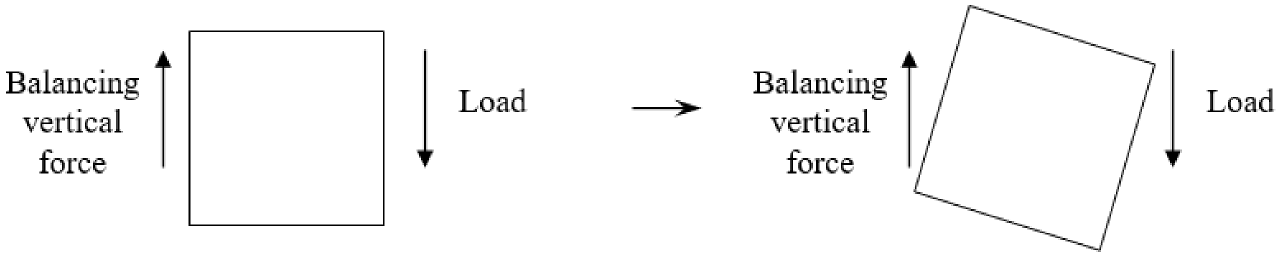
In Class: Take the ruler and have two people hold each end. Apply a small load to the middle to make the ruler bend. 3 Ask the two students if they felt a force on the ends of the ruler. When an affirmative answer is given, challenge the class by asking how they think the vertical load got from the middle of the beam to the ends. After a bit of discussion, bring out the first demonstration.



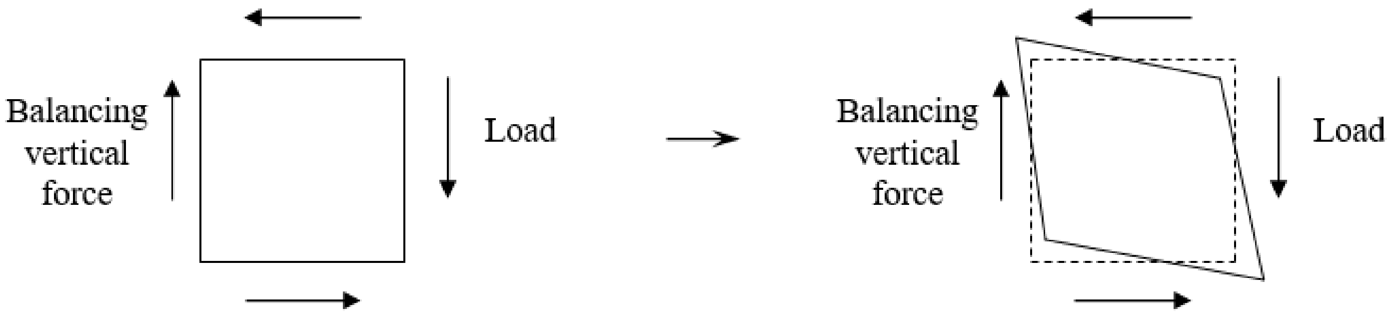


Show the students the demonstrator with the plastic strips attached to the base (cantilever). Ask what they think will happen to the beam and the square in the middle when you apply a force to the free side of the cantilevered beam. Press down on the beam and show how the square deforms (as the pieces of plastic slide). 4 Relate this to the shape of the square on the side of a cylindrical rod.

Ask the class: what is happening to the fibers inside of a solid beam (one not made up of eight strips of plastic strips). Explain how the forces are working in the beam. There is a force applied downwards on the free side of the beam, and therefore a force acting upwards on the other side to put the beam in equilibrium. Ask then how these forces would tend to make the square move if they were the only forces in the beam. Show how the square would rotate with these forces.



In Class: What forces keep this rotation from occurring? There must be horizontal forces equal to the vertical forces that keep the square from rotating. These forces cause the square to deform into a rhombus shape.



Why is shear so important? Shear is the least understood phenomenon. If overlooked, shear forces can cause failure, and they often do. The second demonstration shows why. Hold the four lengths of plastic attached at both ends and once again ask the class what they think will happen if you apply a moment to bend the member. 5

Bend the member and point out the sliding of the sections of the member, how they don't line up at the ends any more and how they separate in the middle when the force is slowly relieved. 6 This is how member will fail at the end of a member (ends of a simply supported beam) when they are acted upon by the resulting internal shear forces caused by a load applied perpendicular to the longitudinal axis. 7 This is also how a vertical load is transferred horizontally along the length of the beam to the usual vertical reaction at the end points, especially in a simply supported beam.

<u>Additional Application</u>: Ask the class if they can think of an example of a material that acts like these sectioned members. Ask if anyone has seen an old wooden bridge that has begun to split at the ends and talk about how wood reacts to shear forces. Because of a wood's grain, it is very strong if forces are applied perpendicular to the grain. But when forces, like shear, are applied along (horizontally) the grain, the wood begins to fail because it splits much more easily along the grain than against the grain.

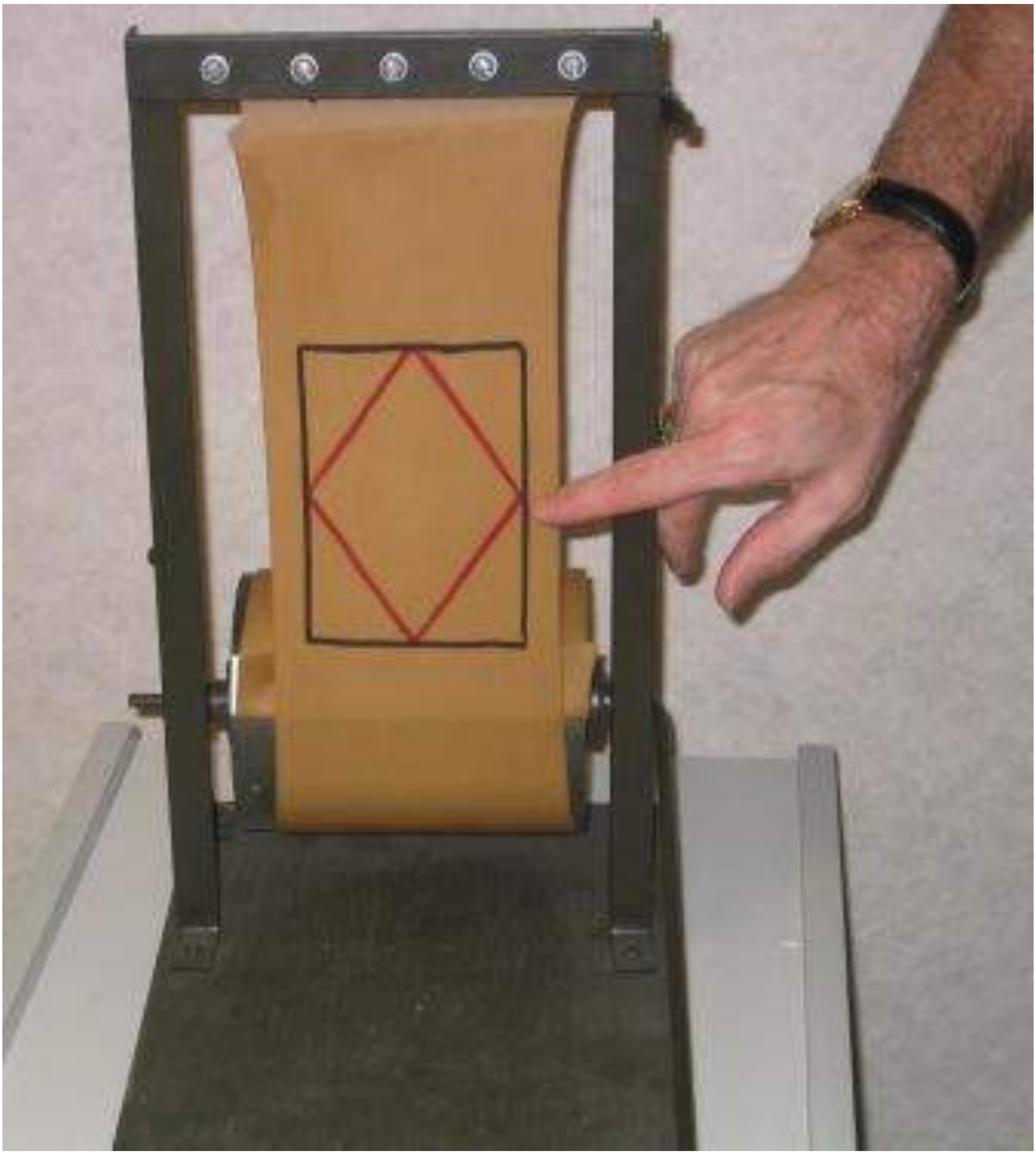
A STRAINGE TRANSFORMATION

MECHANICS

Keywords: Axial, Shear, Strain, Stress, Transverse Plane

Submitted by: Allen Estes

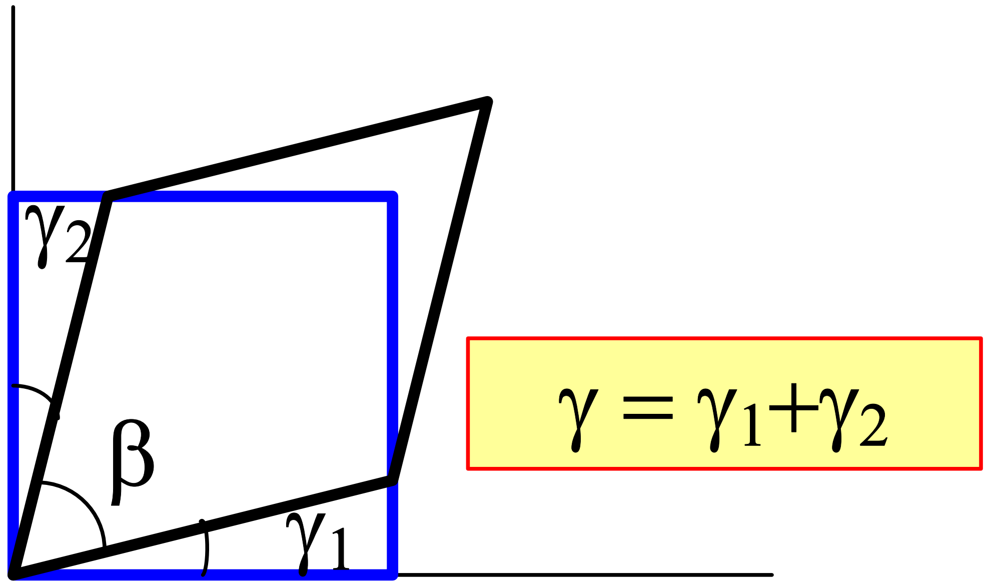
Model Description: A thin rectangular sheet of rubber material is subject to an axial load. Stress blocks are painted or drawn on the rubber material. The stress blocks are oriented on a transverse plane (**black** square) and on a plane 45° from the transverse plane (**red** square). Students have previously learned that only normal stress exists on the transverse plane and the 45° plane experiences the maximum shear stress. As the rubber material is stretched, the students can see that sides on the transverse stress block get longer in the longitudinal direction and shorter in the lateral direction while the angles at the corners do not change. Students can use a ruler to compute the normal strain and Poisson's ratio for the material. Similarly, on the 45° stress block, the lengths of all four sides increase the same amount and the angles change. The angles on the top and bottom corners get smaller and the angles on the left and right corners get larger. This demonstrates that shear stresses and strains exist within an object subjected to an axial load.. This demonstration should take 35 minutes.



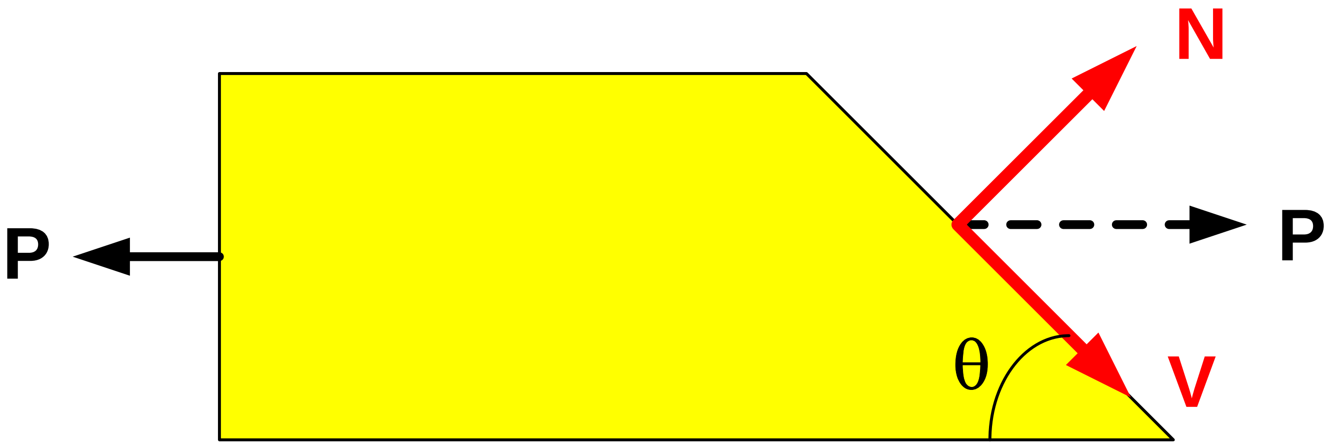
Engineering Principle: Normal strain in the longitudinal direction (ε_{long}) is defined as the deformation per unit length.

$\varepsilon_{long} = \frac{L_f - L_o}{L_o} = \frac{\delta}{L_o}$ where $L_o$is is the original undeformed length, L_f is the final length after a load has been applied and δ is the resulting deformation. Conversely, the width of the stress block is getting smaller. The strain in the lateral direction (ε_{lat}) is computed as $\varepsilon_{lat} = \frac{w_f - w_o}{w_o}$ where w_o and w_f are the initial and final widths of the stress block, respectively. Poisson's ratio (ν) is the ratio between the longitudinal and lateral strains: $\nu = \frac{-\varepsilon_{lat}}{\varepsilon_{long}}$. The shear strain ($\gamma$) is the change in the angle on the stress block caused by the deformation,

$\gamma = \frac{\pi}{2} - \beta = \gamma_1 - \gamma_2$ as shown on the diagram below.



For an axially loaded member, the shear stress and the normal stress are different for different planes.



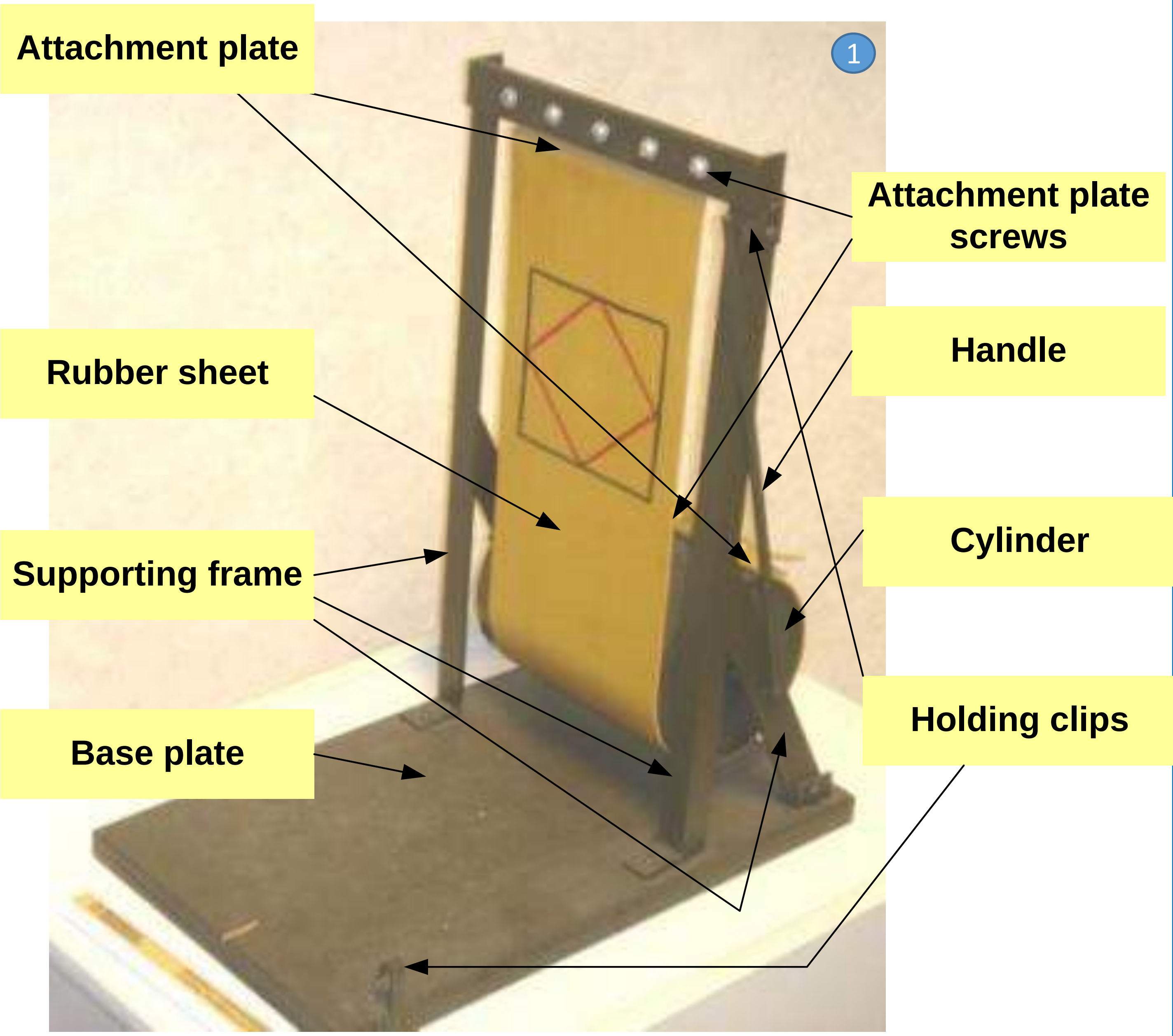
For any given angle (θ) shown on the drawing above, the normal stress (σ) and shear stress (τ) can be expressed as $\sigma = \frac{P\cos^2\theta}{A}$ and $\tau = \frac{P\sin\theta\cos\theta}{A}$ where P is the applied axial load and A is the transverse area of the cross-section. Normal stress is a maximum on the transverse (90°) plane and is equal to $\sigma_{90^\circ} = \frac{P}{A}$ and the shear stress is zero. On a 45° plane, the shear stress is maximum and is equal to $\tau_{45^\circ} = \frac{P}{2A}$ and the normal stress is $\sigma_{45^\circ} = \frac{P}{2A}$. If the Modulus of Elasticity (E) of the material is known and the material is in the elastic range, then the normal stress can be related to the longitudinal strain: $E = \frac{\sigma}{\varepsilon}$.

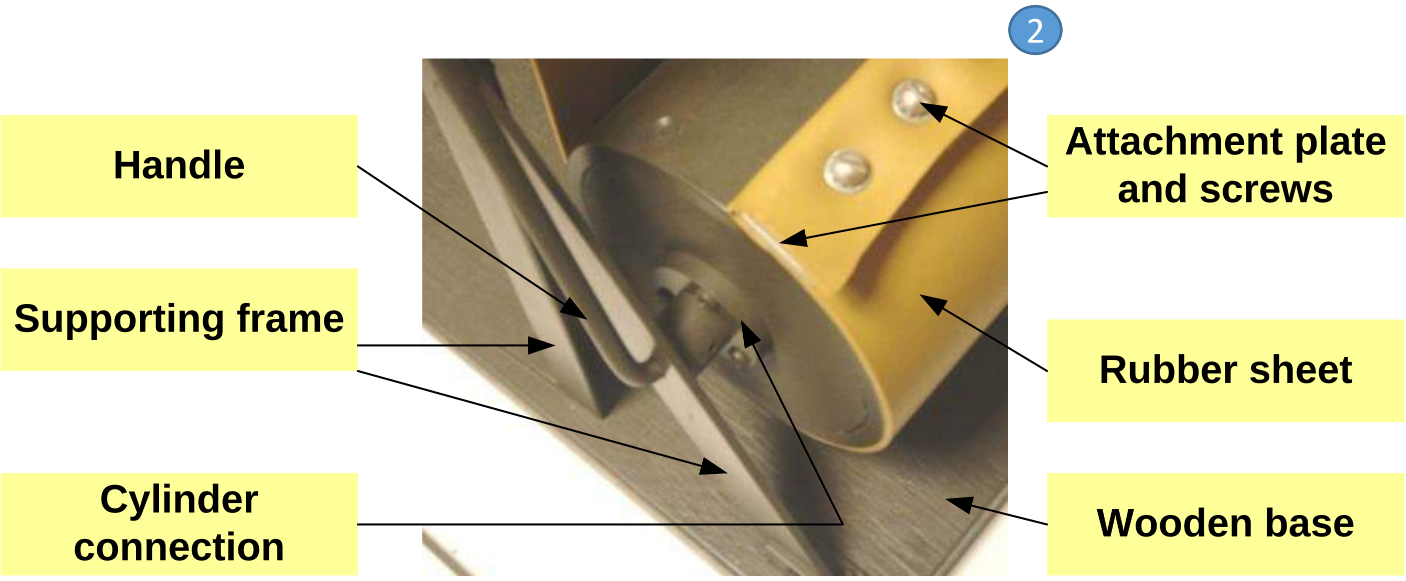
Similarly, the Shear Modulus (G) of the material relates the shear stress to the shear strain, $G = \frac{\tau}{\gamma}$ and the Shear Modulus can be computed as $G = \frac{E}{2(1+\nu)}$.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Thin sheet of rubber material	1	**	A thin sheet (1/16") of rubberized material. Approximate dimensions should be 18" long by 5-1/2" wide. Use permanent markers to draw a 4-3/16" square transverse stress block. Inscribe a 45° 3" square stress block inside the transverse block.
Steel frame	1	**	The rubber is supported by a steel frame consisting of two vertical members (16" long), a top horizontal member (8-1/2" long) and two supporting braces (8" long) . The vertical members are 3/4" by 3/4" by 1/8" angle pieces. The top horizontal member and the braces are 1" by 1/8" plates. The frame members can be connected by welds or small bolts. The frame is connected to the wooden base using screws.
Wooden base	1	**	A 15" by 9" piece of 3/4" thick wood is used as a base for the device.
Cylinder	1	**	A 4-1/2" diameter cylinder is used to hold the bottom of the rubber sheet. The cylinder is supported by the frame and is free to rotate. The cylinder device shown here is made of wood, but a coffee can has been used on previous devices.
Attachment plates and hardware	1	**	The rubber sheet is attached to the top of the structural frame and to the rotating cylinder at the bottom. The rubber sheet should be wrapped around a 1/8" supporting plate (5-1/2" by 1"). Without the plate, the rubber will rip through the supporting screws when a load is applied. Screws or bolts should be used to attach the plates to the steel frame on the top and the cylinder on the bottom.
Handle	1	**	A 1/4" diameter handle is attached to the center of the cylinder and bent at a 90° to rest at the top of the steel frame. The length of the handle is 12" measured from the center of the cylinder. The load is applied to the rubber material using the handle. The user pulls on the handle which causes the cylinder to rotate which in turn stretches the rubber membrane. Photos below offers a better view of the handle/cylinder connection. 1 2
Holding Clips	1	**	The handle is secured in the unloaded and loaded configuration using holding clips as shown in the photo. One holding clip is attached to the top of the supporting frame and one is attached to the wooden base using screws.

** The total cost and build time is $50-75 and 2-3 hours. **


1
Attachment plate
Attachment plate screws
Rubber sheet
Handle
Supporting frame
Cylinder
Base plate
Holding clips

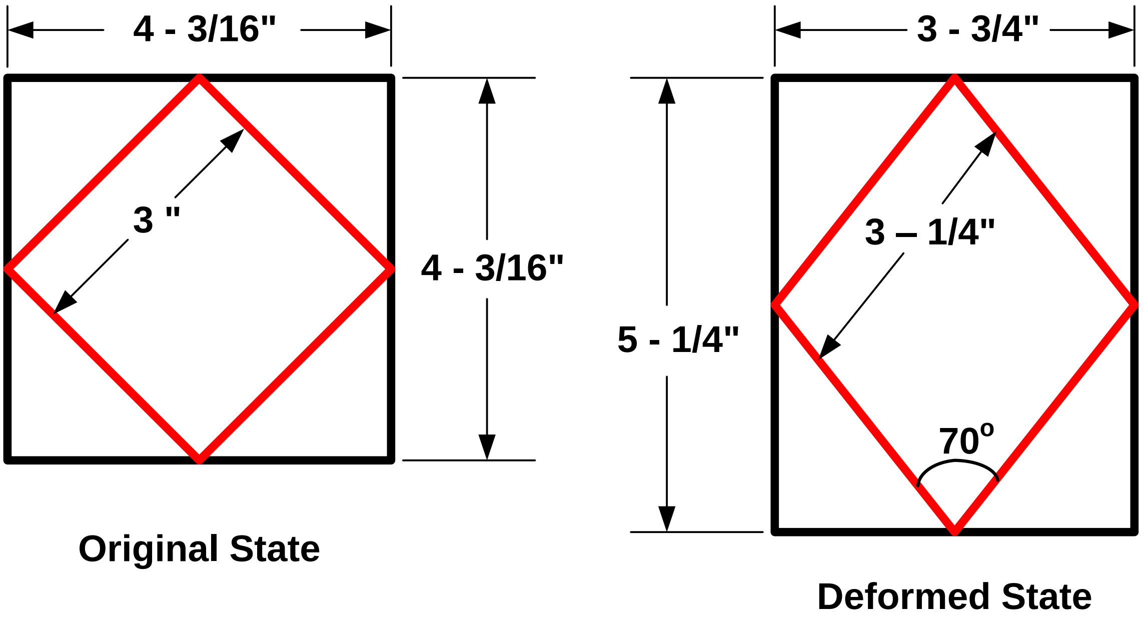

2
Handle
Attachment plate and screws
Supporting frame
Rubber sheet
Cylinder connection
Wooden base

APPLICATION

Before Class: Bring the axial strain device, a ruler and a protractor to the classroom.

In Class: Measure the lengths of the undeformed stress blocks with a ruler and record the results on the board. 3 Verify with the protractor that the angles on the corners of the stress blocks are 90°. Pull on the handle which rotates the cylinder and stretches the rubber membrane. Lock the handle into the holding clip in the wooden base. Measure the new lengths of the deformed stress blocks and use the protractor to record the angles at the corners of the stress blocks.

For a short demonstration, the students will be able to see the qualitative difference in the two stress blocks as they change from the undeformed to the deformed position. Getting the students to describe what they see and attempting to relate this to stress-strain theory is an effective 2 minute learning demonstration. For a more detailed demonstration, make some computations based on the measurements and assess whether they support the theory. For the device shown in the photo, the measured results and sample calculations are shown below:



Initial data Measurements:

$$L_o = 4.188\ inches \qquad L_f = 5.25\ inches$$
$$w_o = 4.188\ inches \qquad w_f = 3.75\ inches$$

Note that the transverse normal stress should be about double the normal stress on the 45° plane. Similarly, the normal stress and shear stress on the 45° plane should be equal. Given the precision of the measuring instruments used (ruler and protractor), these results are not bad.

Additional Application: Rather than looking in a reference book for the Young's Modulus value for rubber, you could use this device to compute the approximate value. You have already computed the longitudinal strain value when the handle is in the extended position. Attach the handle to a spring loaded scale (similar to those used to weigh a caught fish). Determine how much force it takes to hold the handle in the extended position. Compute the force on the rubber membrane (P_{mem}) using the force that it takes hold the handle in place (F_{handle}) $P_{mem} = \frac{F_{handle} \times L_{handle}}{r_{cylinder}}$ where L_{handle} is the length of the handle from the center of the cylinder to the point where the spring scale is attached and $r_{cylinder}$ is the radius of the cylinder. If the rubber membrane is 5-1/4" wide and 1/16" thick, then their product is the cross-sectional area of the rubber membrane (A_{mem}). The normal stress on a transverse plane is $\sigma_{long} = \frac{P_{mem}}{A_{mem}}$ from which the Modulus of Elasticity (Young's Modulus) can be computed as $\mathrm{E} = \frac{\sigma_{long}}{\varepsilon_{long}}$.

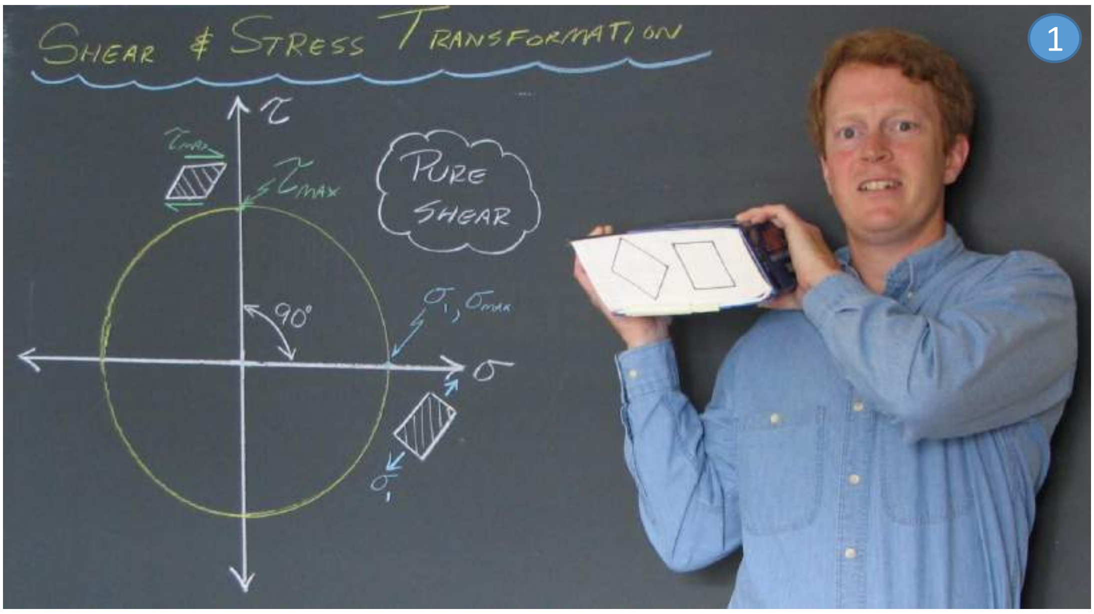
THE BIG BOOK OF SHEAR

MECHANICS

Keywords: Shear, Stress - Strain Transformation

Submitted by: Led Klosky

Model Description: Students often have difficulty with shear and stress/strain transformation. To give a quick demonstration of pure shear and stress transformation, blocks are drawn on the side of a BIG book to show the effects of shear and transformation of axes. 1 This demonstration should take 3-5 minutes.



Engineering Principle: Shear occurs when parallel planes within an object tend to move laterally with respect to each other, rather than away or towards each other, as occurs with more-familiar normal stresses and strains. The most commonly cited examples of this phenomenon are seen in bolts or other connections where the connected surfaces tend to move laterally with respect to one another. Unfortunately, the connection case poorly illustrates the more usual case of shear caused by a general state of stress. To illustrate the more common case, blocks, similar to stress blocks, are drawn on the pages of a stiff-spined book and the book is placed under pure shear. By offsetting the two blocks by 45 degrees, one block is placed in pure shear, while the other block sees no shear at all. This is best illustrated using Mohr's circle.

REQUIRED ITEMS

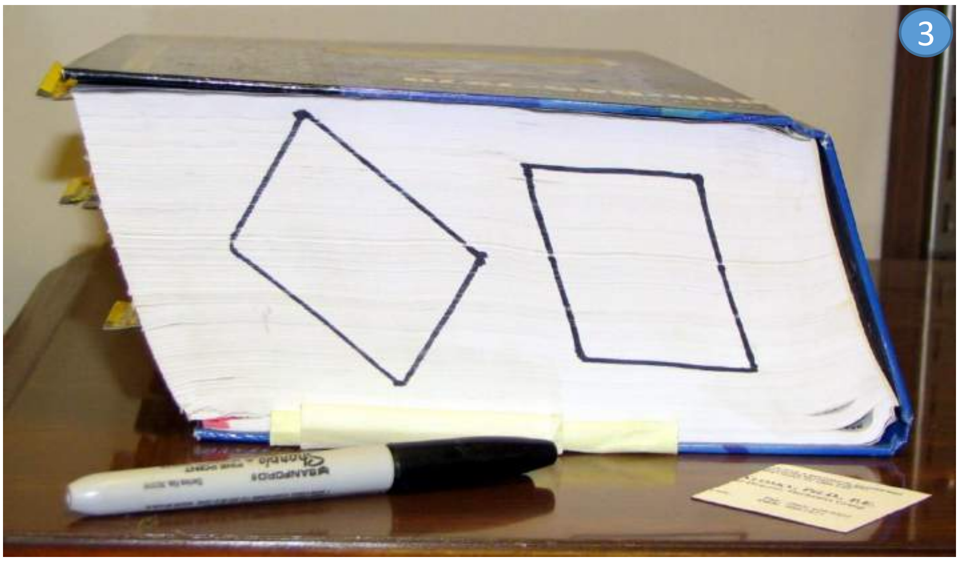
Item	Qty	Cost and Build Time	Description/Details
Large book with a stiff spine	1	Varies with book size if not on hand	The book must have a stiff spine so that the imposed motion will cause pure shear.
Markers	1	$1	A black permanent marker works best. Ensure that marks are dark against white pages so the students can see the demonstration from all areas of the classroom.
Cardboard square	1	$1; 1 minute	Business cards or cereal boxes can be easily cut into a square guide for the demonstration.

APPLICATION

Before Class: Cut out a square of stiff cardboard, and draw careful squares at the orientations shown on the same end of the book. 2 Students will suspect a trick, so make sure they can see everything at the same time. Ensure the squares are offset by 45 degrees so that one is in pure shear and the other is at the orientation of the principal stresses.

In Class: Point out to the students that the marks on the pages are the same size, and the only change is the orientation of the marks. Discuss the state of pure shear in detail, and then point out the fact that one of the blocks is in pure shear and one has no shear, even though they are drawn on the same pages. Draw Mohr's circle for the case of pure shear, with the circle centered at the origin, to illustrate how normal stresses still exist, and where they should expect to find them.

Observations: Students should observe that the magnitude and type of stress varies according to the orientation of the axis system. 3 Further, they should note that maximum shear and maximum normal stresses lie 45 degrees apart in a given stress state, 90 degrees on Mohr's circle.



Additional Application: Many students will continue to struggle with this concept throughout the semester. Keep a marked up version of the book in the classroom and office for reference when a student is struggling with the "what does it all mean?" part of stress transformation. It also helps to discuss how some materials, like the book, resist different type of stress differently, so it's important to quantify all the stress states. For instance, the book takes compression very well, shear somewhat poorly, and simply cannot resist tension normal to the pages. Thus, both the magnitude and orientation of the stresses within an object are key analysis outputs and design inputs.

THERMAL EXPANSION

MECHANICS

Keywords: Contraction, Expansion, Strain, Stress, Thermal

Submitted by: Ronald Welch

Model Description: This physical model demonstrates thermal expansion for different metals. This demonstration should take 10-15 minutes.

Engineering Principle: When materials, especially metals, are exposed to heat, they expand at different rates. The reverse is also true in that cold temperatures tend to cause material contraction. The amount of expansion/contraction may be small, but if not taken into account in the design of structures and/or machine parts, the resulting expansion/contraction could result in excessive strain/stress.

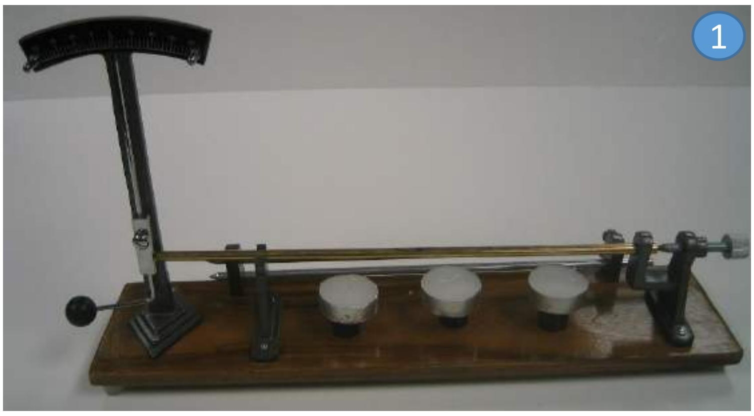
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Pyrometer	1	$50	This is the apparatus used to demonstrate how metals expand with heat. The entire apparatus is about 16 inches long.
Candles	3	$3	Small candles are used to heat up the metals. The pyrometer calls for only one candle; however, the resulting change and time to see the change in the steel was excessive. Three candles were ideal to create perceptible change in a reasonable amount of time.
Lighter or matches	1		A lighter or matches is necessary to light the candles.
Supports	As needed	$3; 2 minutes	The magnets raised the candles closer to the rods to increase the amount of heat applied to the metal rods.
Metal Rods	3	$25-30	Three types of metal rods are part of the kit used to show different expansion rates: brass, steel, and aluminum.

APPLICATION

Before Class: Test the apparatus to see that it works properly with the equipment used. Be sure that it is safe to use a candle flame in class.

In Class: Set up the apparatus 1 and begin to explain how heat affects materials by making them expand. Show the class the three rods and ask which they think will expand most. Put the first rod in the apparatus, set the measurement to zero using the screw on the right-hand side 2, and place the lit candles underneath the rod. 3

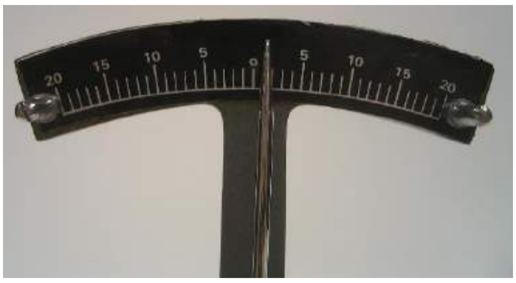


In any order, heat up each of the rods for about 10 minutes and make a note of how much the length of each changed. This experiment can be occurring while you are presenting the theory associated with thermal expansion. The students should see the brass expanding the most, then the aluminum, and the steel expands least.

Brass

Aluminum

Steel



Additional Application: Using the results of the demonstration, the professor can lead a discussion on the proper selection of materials and how designers plan for associated expansion/contraction. Some examples are the use of expansion joints in bridges and buildings, tolerances in engine parts, steel vs brass (can select any types of materials for comparison) for a material type to decrease the amount of expansion/contraction associated with temperature.

THIN WALL PRESSURE VESSELS – BALLOONS!

MECHANICS

Keywords: Hoop Stress, Pressure, Thin Wall Pressure Vessel (TWPV)

Submitted by: Led Klosky

Model Description: This is a simple demonstration of the basic principles underlying the behavior of thin-walled pressure vessels (TWPVs). A balloon or balloons are used to show that hoop stresses are twice as high as longitudinal stresses in cylindrical pressure vessels. This demonstration should take 8-10 minutes.

Engineering Principle:
The basic derivation for TWPV behavior states that for a cylindrical pressure vessel

$$\sigma_{hoop} = \frac{P \times r}{t}$$

$$\sigma_{longitudinal} = \frac{P \times r}{2t}$$

where the hoop stress is equal to the pressure times the inner radius divided by the wall thickness. The longitudinal stress is exactly half the hoop value. Further, according to Hooke's Law, the strain will follow the stress, so observed deformations are indicators of the magnitude of stress.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Party Balloons	10-20	$10; 20 minutes	Both round and cylindrical. Spheres should be 10" minimum diameter when inflated, and the length of the cylindrical balloons should be about 5 times the circumference. Choose really big balloons for big lecture halls.
Inflation Device	1	$25	This demo uses a Super Soaker filled with air rather than water. Either way, the device needs to be able to fill the balloon rapidly to avoid "dead air". 1
Marker/Pen	1	$3	You'll have to experiment with this somewhat to get a clear, dark mark without having the carrier of the ink weaken the balloon

1

APPLICATION

Before Class: Prepare the balloons by drawing a square stress block midway down the length to negate the effects of the ends. 2 Be careful drawing the square; ensure that the sides are equal with 90° corners and the lines are very bold. If the lines are not dark enough, they will be very hard to see after the balloon is inflated, because they fade when they stretch. Regular ball-point ink pens work well for drawing the stress block. Test this out a few times before going into the classroom to make sure the marks and the inflation device won't fail you when it counts.

In Class: Have fun with the demonstration and play up the inherent party nature of balloons. Several pre-marked, deflated balloons of each type are displayed at the start of class. Show the students the square stress blocks on the deflated balloon and ask the students what shape the square will be after the balloon is inflated for each balloon type. Will the sides be the same length? The corners still 90°? The balloons are then inflated and the behavior is observed.

Observations: The students should observe that on a spherical balloon, the stress block remains square, with 90° corners. This demonstrates that the magnitude of the stress in both the longitudinal (along the length of the balloon) direction and the hoop (around the circumference) direction are the same. On the cylindrical balloon, the students should observe that the initially square stress block has deformed into a rectangle, with the longitudinal deformation being half as great as in the hoop direction. This demonstrates that the magnitude of the hoop stress is twice that of the longitudinal stress. For both balloons, the persistence of 90° corners demonstrates that there is no shear stress acting on the stress block. The lack of any shear deformation shows that the stress blocks are oriented in the principal stress directions in both cases.

Additional Application: Ask student volunteers to blow up the balloons, having purchased balloons that were difficult to inflate. The students have always succeeded in blowing up the balloons, although usually only after multiple attempts. Do not choose students who smoke or have lung ailments for this part of the demonstration, as they may injure themselves trying to inflate the balloons. Next, ask the students if they'd like to see you blow up the balloon. The students are usually quite eager to see what shade of red the instructor's face will turn during the attempt, but are surprised when the instructor produces a hidden Super Soaker water gun fully charged with air and easily inflates the balloon. Two embedded lessons within this demonstration are the spherical pressure vessels on the Super Soaker (why did they choose spheres?) and the fact that pre-yielding the latex balloons by stretching significantly weakens them and allows for easy inflation.

THIN WALL PRESSURE VESSELS – HOT DOGS!

MECHANICS

Keywords: Hoop Stress, Pressure, Thin Wall Pressure Vessel (TWPV)

Submitted by: Matt Morris and Led Klosky

Model Description: This is a simple demonstration of the basic principals underlying the behavior of thin-walled pressure vessels (TWPVs). A hot dog is used to show that hoop stresses are twice as high as longitudinal stresses in cylindrical pressure vessels and failure occurs along the length of the hot dog. The failure that occurs in the hot dog is due to hoop stress. This demonstration should take 8-10 minutes.

Engineering Principle:

The basic derivation for TWPV behavior states that for a cylindrical pressure vessel

$$\sigma_{hoop} = \frac{P \times r}{t}$$

$$\sigma_{longitudinal} = \frac{P \times r}{2t}$$

where the hoop stress is equal to the pressure times the inner radius divided by the wall thickness. The longitudinal stress is exactly half the hoop value. Therefore, a thin-walled pressure vessel is expected to fail due to hoop stress long before failure due to longitudinal stress.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Hot Dog	Varies	\$2-15; 20 minutes	At a minimum, use one regular hot dog per class. To enhance the demo provide one hot dog per student. Put a small slit in the hot dog (if necessary) to get it to fail from hoop stress.
Microwave	1		
Refrigerator	1		Ensure your materials remain fresh!
Hot Dog Rolls, Condiments, Aluminum Foil	Lots	\$20	These items are optional, but will enhance the presentation of the training aids.

APPLICATION

Before Class: Heat the hot dog in the microwave until it's fully cooked. 1 Check to ensure the hot dog clearly failed down the longitudinal axis due to hoop stress. 2 You may have a defective hot dog which fails due to an improper seal at one end, so be prepared to cook more than one.

In Class: Ask the class for different examples of thin walled pressure vessels. Steer the students into giving examples of foods which behave as TWPV's. After hearing a few examples, try to get the student to say, "hot dog". At this point, pull the hot dog out and show the students.

Observations: The students should observe that the hot dog, cylindrical in shape, failed down it's length. This demonstrates that when the magnitude of the internal pressure increased, the hoop stress increased at twice the rate of longitudinal stress. Therefore, in a cylindrical TWPV, hoop stress will cause failure before longitudinal stress.

Additional Application: Don't merely take the hot dog out to show the students! When it's time to display the hot dog, the professor usually complains that he/she is really hungry. To make matters worse, there was someone working in the classroom earlier and threw out some food in the trash can. At this point the professor grabs the trash can to see if there's any leftover food. To his/her surprise there is a half eaten hot dog with mustard and ketchup in the trash. At this point the professor says, "Wait a minute, this hot dog reminds me of a thin walled pressure vessel! Let's see what happened when it was heated up!" At this point the hot dog is revealed to the students and the hoop stress discussion begins. Usually the students suggest eating the hot dog out of the trash. Although optional, eating the hot dog really gets the attention of the students! Afterwards, hand out one pre-heated hot dog to eat student to observe the hoop stress failure.

THIN WALL PRESSURE VESSELS

MECHANICS

Keywords: Cylindrical, Hoop, Longitudinal, Stress, TWPV

Submitted by: Ronald Welch

Model Description: These physical models demonstrate basic principles underlying the behavior of thin-walled pressure vessels (TWPVs). Two models of TWPVs are used to explain forces inside of TWPVs. This demonstration should take 10-15 minutes.

Engineering Principle: The basic derivation for TWPV behavior (when $\frac{r_{in}}{t} > 10$) states that for a cylindrical pressure vessel

$\sigma_{hoop} = \frac{Pr}{t}$ and $\sigma_{longitudinal} = \frac{Pr}{2t}$

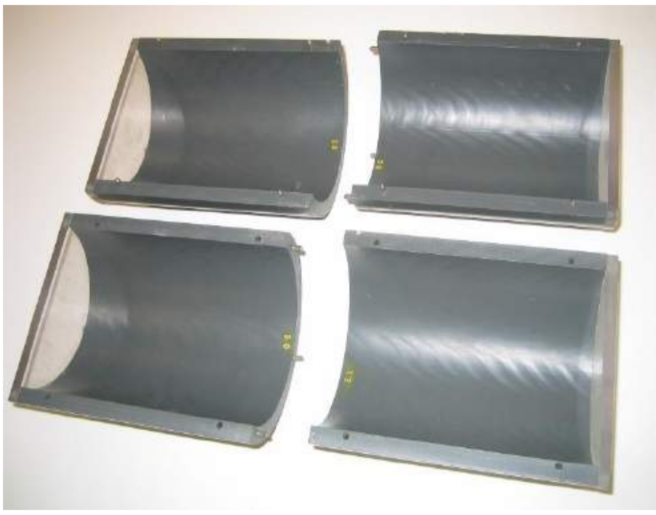
where the hoop stress is equal to the pressure times the inner radius divided by the wall thickness. The longitudinal stress is exactly half the hoop value. Therefore, a thin-walled pressure vessel is expected to fail due to hoop stress (failure plane along the length of the cylinder) long before it will fail due to longitudinal stress.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Wooden Model	1	\$20; 60 minutes	A wooden cylinder about 3” in diameter and 6” long. The cylinder is cut in half along the longitudinal axis. Pegs are put through one half and holes are drilled into the other so that the two halves can be put together and taken apart easily.
Plastic Model	1	\$30; 60 minutes	Cylinder is hollow and made of four pieces. The cylinder is approximately 12” long and 4½” in diameter. It is cut in half twice, once along the longitudinal axis and once through the cross-section. The four pieces fit together with pegs that protrude from the side of each piece. The top and bottom of the cylinder are made of clear plastic and screwed onto the opaque sides (grey in this case).
White Pen or Marker	1	\$2	The wooden model has the planes and stresses drawn on it with white pen to better demonstrate how stresses flow through a cylinder.

APPLICATION

Before Class: Paint the wooden model black and draw the forces and label the planes with the white pen or marker. Make sure the two models are easily taken apart and put back together so there are no issues during class.



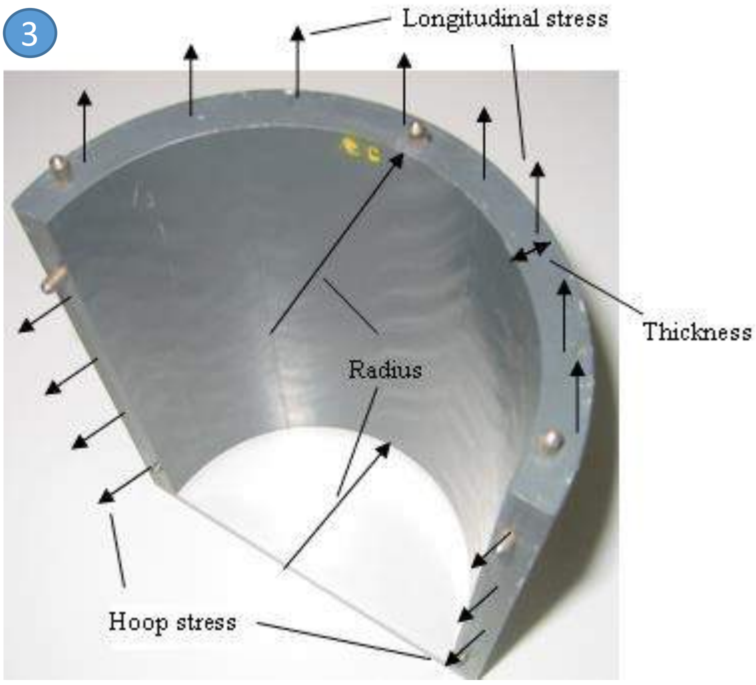
In Class: Show the students the two models and ask: how is the internal cylinder pressure carried by the cylinder? Use the two models to show/explain the two different kinds of stress: hoop and longitudinal. Hoop stress is applied around the circumference, while longitudinal stress is applied along the length of the cylinder. The wooden model shows the two planes in which the internal stress act. The hoop stress is applied on the transverse plane 1, while the longitudinal stress is applied on the longitudinal plane 2. This physical model physically represents the planes the internal pressure acts upon.

<u>In Class</u>:
Using the plastic model, show how a TWPV can fail due to these two stresses. When a vessel fails due to longitudinal stress, it fails along a circumferential plane.

When a vessel fails due to hoop stress, it fails along a longitudinal plane.

Additional Application: Derive the formulas for TWPVs directly from the plastic cylindrical model using only a section of the cylinder.

3



Using the model, help the students visualize how the internal pressure acts on the cylinder and generates internal stresses in the cylinder walls. Pull from the students that there are both internal stresses acting in the longitudinal and circumferential directions.

To solve for the longitudinal stress, we use an equation of equilibrium for the forces due to generated internal cylinder stress and the force due to internal pressure. Those forces are best seen when the cylinder is cut perpendicular to the longitudinal axis exposing the circular hollow cross section of the cylinder and the circular area of the pressurized fluid in the cylinder. The force due to the resulting longitudinal stress is equal to the stress multiplied by the area of the wall of the vessel around the circumference. The force due to internal pressure is equal to the pressure multiplied by the area of the fluid plane exposed by the cross-sectional cut of the cylinder.

$$\sum F_{long} = 0 \qquad \sigma_{long}(2\pi rt)\text{-}p_{long}(2\pi r^2) = 0$$

$$\sigma_{long} = \frac{pr}{2t}$$

To solve for hoop stress, we use an equation of equilibrium for the forces due to generated internal cylinder stress and the forces due to internal pressure. Those forces are best seen when the cylinder is cut parallel to the longitudinal axis exposing the oblong hollow cross section of the cylinder and the oblong area of the pressurized fluid in the cylinder. The force due to hoop stress is equal to the stress multiplied by the exposed area of the wall of the cylinder along each side of the cylinder. The force due to internal pressure in that plane is equal to the pressure multiplied by the area of the fluid plane exposed inside by the longitudinal cut of the cylinder.

$$\sum F_{long} = 0 \qquad \sigma_{hoop}(2t\Delta x)\text{-}p_{hoop}(2r\Delta x) = 0$$

$$\sigma_{hoop} = \frac{pr}{t}$$

Both of these cuts and the exposed internal cylindrical stress are seen above 3. From these equations, we determine that the hoop stress is two times as great as longitudinal stress, thus a thin-walled pressure vessel would normally fail due to hoop stress before longitudinal stress.

TOWER OF TORQUE

MECHANICS

Keywords: Shear, Stress, Torsion

Submitted by: Led Klosky

Model Description: Thrill your students with Tales of Torque using the versatile Tower of Torque! 1 In its simplest form, the device allows students to predict and then measure the capacity of a simple bolt, modeled as a rod in torsion. This demonstration should take 25-30 minutes.

Engineering Principle: For cylindrical rods in torsion, the maximum shear stress experienced is seen at the outer surface, and for materials in the elastic range the shear stress is computed using the expression

$$\tau = \frac{T \times c}{J}$$

where the maximum shear stress τ is equal to the applied torque T times the distance from the neutral axis to the outer surface of the rod, c, divided by the polar moment of inertia, J. The students should observe that the bolt undergoes permanent deformations when the measured torque on the bolt is computed to cause a shear stress at or somewhat above the published yield stress in shear for the material of which the bolt is made. This demonstration ignores the fact that the sample is under a combined load rather than a pure torsional load in this demonstration. Don't bring that up, but be ready to discuss it.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Tower of Torque	1	$75; 2 hours	A steel base plate with a 1-inch-square steel "mast" projecting from the base. The top of the mast is capable of receiving a real or simulated bolt. Complete plans are included in "Additional Application" below. They may seem a little complex, but the finished product is capable of other demonstrations as well.
Torque Wrench	1	$25	The torque wrench should have a large dial, and the failure torque for the chosen sample should be roughly half the total range of the wrench. It only helps a little if the wrench has a maximum value indicator (a follower).
Torsion Samples	Various	$25-50	Samples consist of 1/2" aluminum or other hex stock turned down to a quarter of an inch in the shank. The samples should be tested thoroughly and a proposed configuration, though certainly not the only one possible, can be seen on page two of the plans.

APPLICATION

Building the Model: The demonstrator is actually fairly straightforward, and measurements can be seen in the plans. The device basically consists of a steel baseplate normal to which a 1" square steel mast is attached by welding. Near the peak of the mast, at a recommended distance of 30" above the base, a square hole is milled to accept the torsion samples. Don't worry too much about making the milled hole exactly square, as the sample will not make contact with the corners of the square since it is a hex. If you like, leave the milled hole closed at the back to facilitate keeping the samples positioned right. 2

Before Class: Secure the base of the demonstrator to a desk or workbench somewhere in the classroom where it will be highly visible to all the students. To save time and raise curiosity, mount the sample in the demonstrator prior to the beginning of class. Check out the direction of the torque wrench to make sure that you rotate it the right way when the moment comes, as not all torque wrenches are bi-directional. Make sure to test the whole apparatus at least once prior to use. There's nothing worse than demonstrating that theory has no bearing on reality!

The Samples: The key property of the samples is that the shafts must be turned down to the point that they can be readily failed in torsion using something like half the total available capacity of the wrench you choose. Practice, practice, practice! Sample strength varies even within the same hex rod, so make sure that the sample will do what you want it to do when the money is down. Mark the samples with a line along the shaft so that the permanent set in the samples due to yielding can be directly observed by students. 3

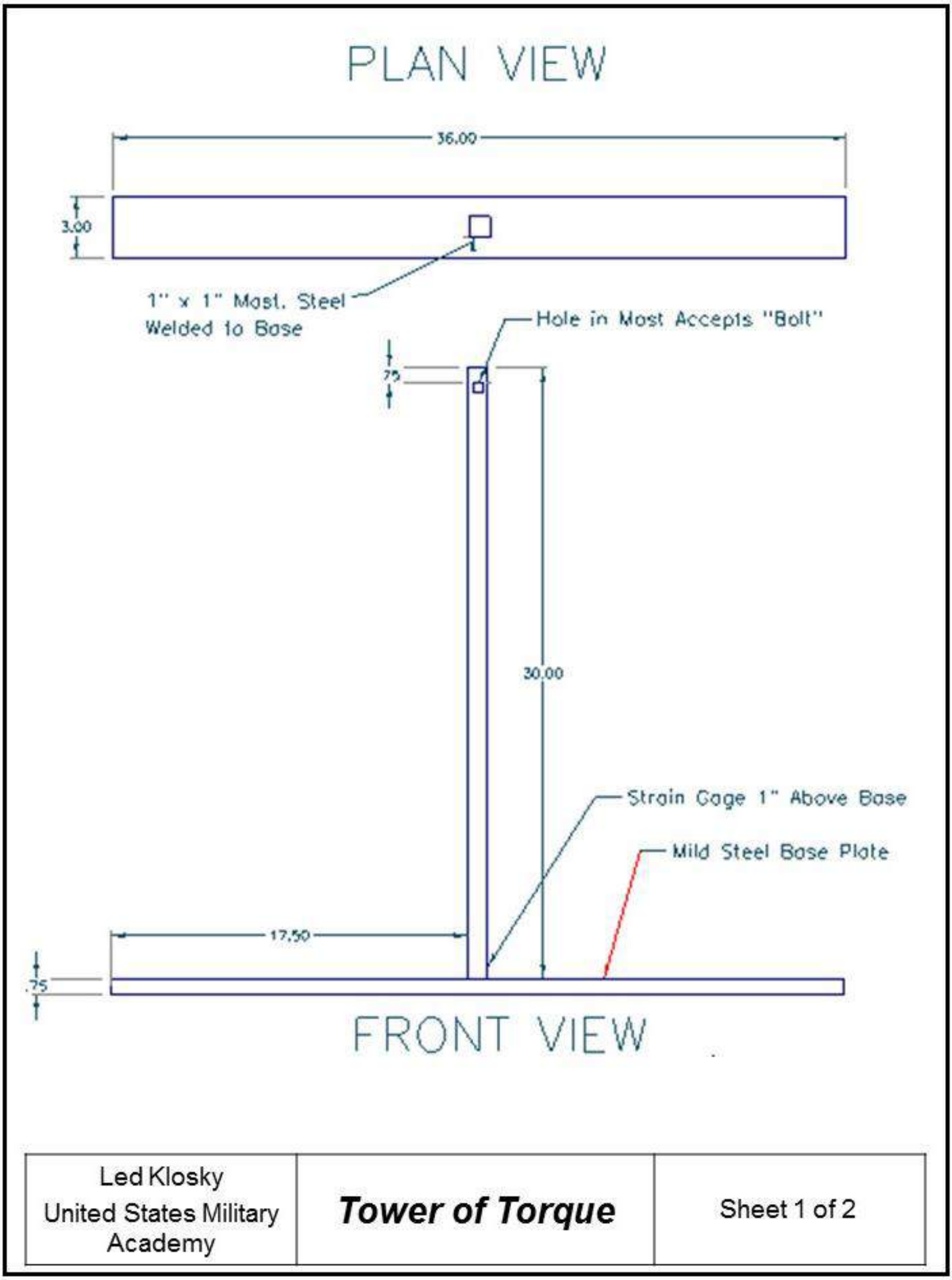
In Class: The procedure can be broken into the following steps:

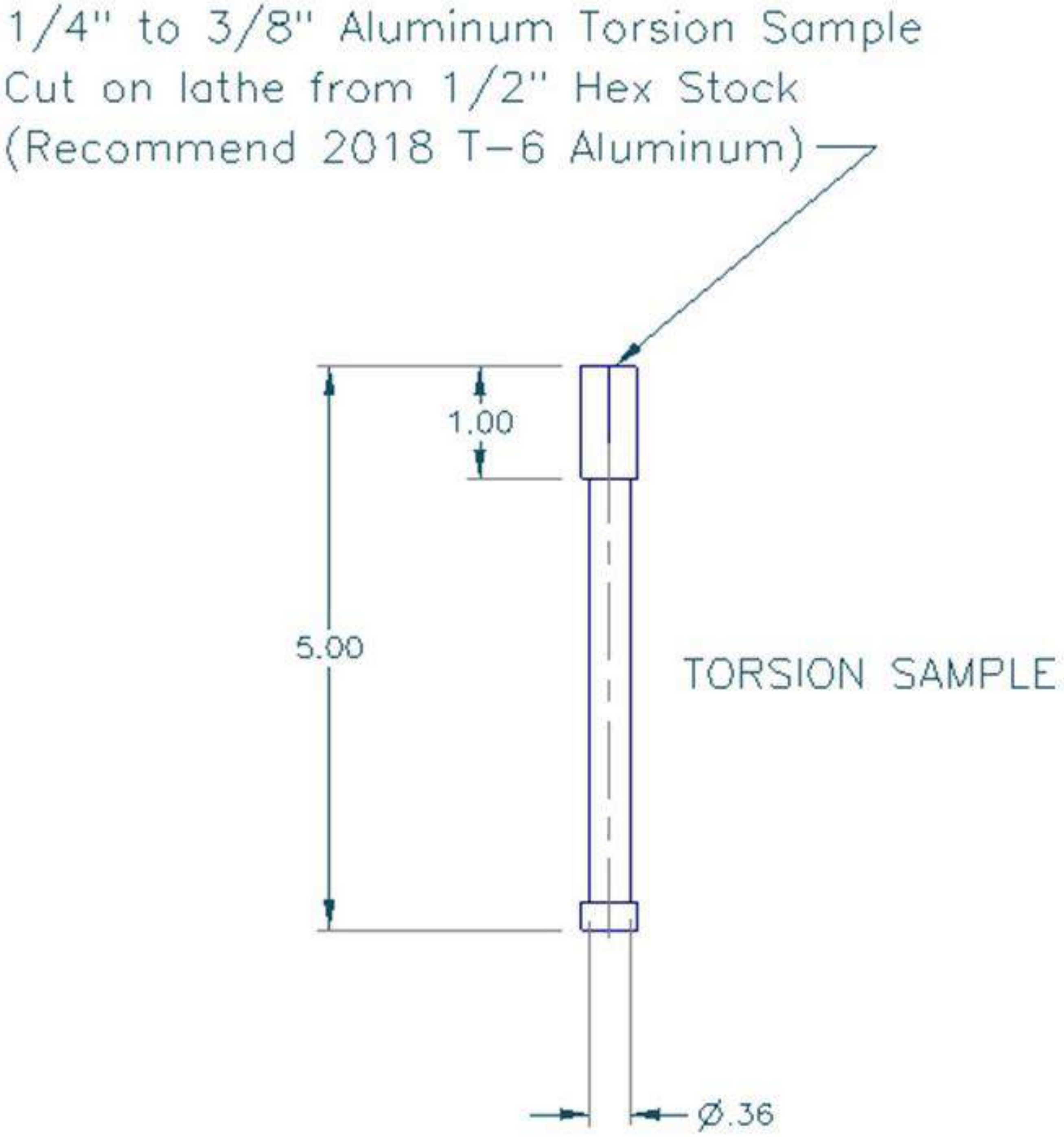
1. If time is plentiful, ask the students what they think about the demonstrator, and see if they can guess what the demonstration is.
2. Have the students compute the minimum applied torque required to cause yielding of the sample. Dig into the fact that the measured torque will likely be higher than the minimum computed value and why. Consider discussing 95% confidence limits if time is available.
3. Slowly apply torque to the sample, having a student call out values as they increase. Try to observe the onset of yielding, and show the students the deformed line on the bolt indicating permanent (non-elastic) deformation.
4. After observing yielding, continue to twist the bolt all the way until failure.
5. Show/pass around the failed part, and discuss what they just saw.

Be careful not to try to measure the angle of twist using the torque wrench handle, as the angle through which the handle moves is larger than that of the bolt (there's a spring in the wrench for measuring the torque!). Further, holding the point of contact of the bolt and wrench steady with your hand helps lower the effects of the combined load on the sample.

Observations: Students should observe that the basic equation for torsion allows for a good estimate of the actual torque necessary to fail a bolt with a wrench. They should also observe that permanent deformation can take place in thin parts through the application of very little torque.

Additional Application: More fun and drama can be added to this class by adding the "Helicopter Mechanics" scenario. Basically, you describe a scenario in which a helicopter maintenance person feels it is necessary to get an aluminum bolt "good and tight". Then, while turning the sample with the wrench at or over the predicted failure torque, say to the class "It must really be getting tight and strong now!". They will realize that tightening the bolt further will really just weaken it, causing the fiery death of the very pilot the mechanics was trying to protect. This emphasizes the key points that 'Knowledge is power' and that engineers need to speak up when they see something being done wrong or dangerously, because they may have unique understanding or knowledge that can prevent tragedy.





Led Klosky United States Military Academy	***Tower of Torque***	Sheet 2 of 2

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STATICS

THE SKI GONDOLA – CONCENTRATED CABLE LOADS

STATICS

Keywords: Cable, Equilibrium, Point Load, Pulley, Two-Force Member

Submitted by: Tom Messervey

Model Description: This physical model demonstrates how cables subjected to concentrated point loads establish equilibrium through geometry – i.e., the slope of each cable segment will change (as will the support reactions) as different loads are placed on the cable. This demonstration should take 10-20 minutes.

Engineering Principle: Cables subjected to concentrated loads are a great example of using static equilibrium to solve real-world problems. The solution method for this problem highlights many fundamental lessons in statics. Basic observations include that cables are two-force members that can be treated just like truss members, that the horizontal component of the tension is equal across all segments, and that the maximum tension must be in the segment with the greatest slope.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Rope or Cord	Any amount	$10-20	Size and cost will vary depending on the size of the model constructed.
Weight	2-3	$10	These weights will act as the point loads on your supported cable.
Measuring tape or ruler	1	$2-15	Used to establish the geometry and solve for the tensions in the system.
Support System	1	$15-50; 30 minutes	Using wood or metal, build a rigid support system to span the cable and support the weights acting on the cable.
Pulley	1	$10	**Only needed as part of the Additional Application**

APPLICATION

Before Class: Build your support structure, tie off both ends of the cord, leave some slack, and hang the weights. Have your measurements and numerical values preplanned to simplify the problem solving process, but also be willing to allow the students to manipulate the weight values and locations within the system.

In Class: Keep a measuring stick nearby so that the students can measure the geometry of the system. 1 This can be used as an in-class problem where the students solve for the tension in the various segments of the rope, thereby realizing that when the loads are tied off, the tension varies in the rope. 2 It can also be demonstrated using a spring loaded scale at one end that as the rope shortens (taking the “belly” out of it), the tension goes up since the weights to be supported act only in the y-direction, and the y-component of the force at the ends must remain constant even as the angle of inclination goes down, causing a large increase in the x-component of the force.

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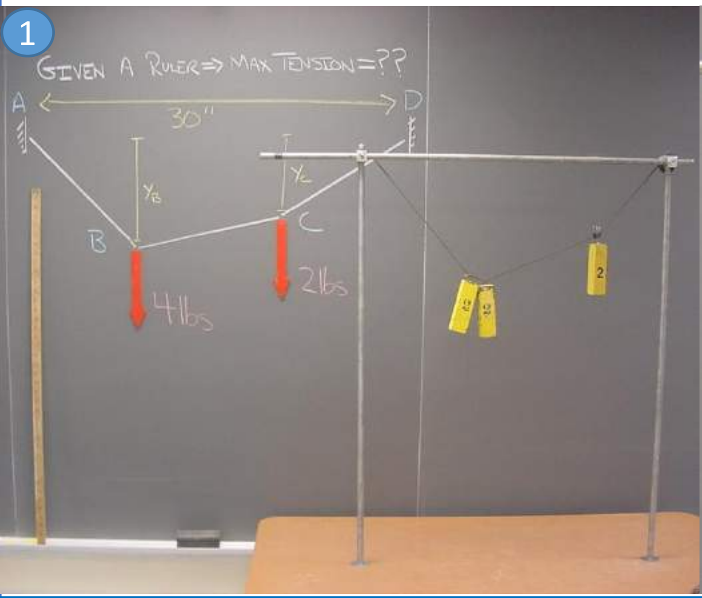

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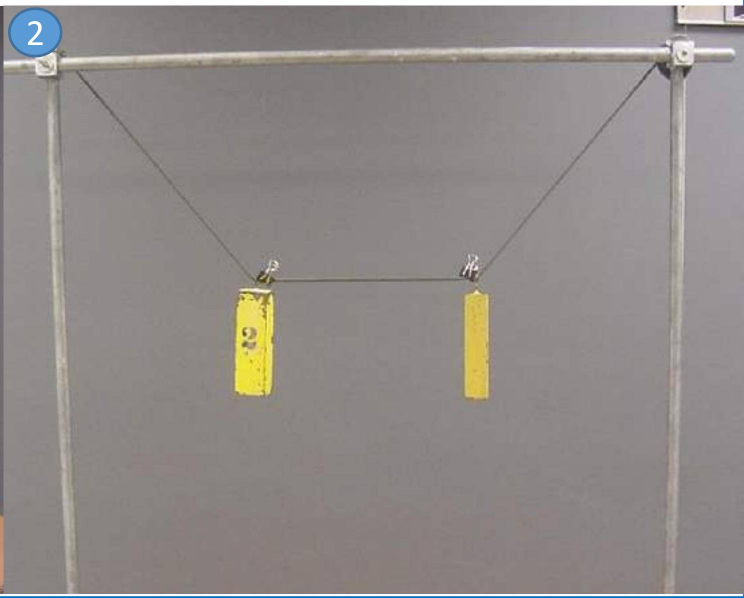

Additional Application: Construct one model that looks similar to a problem being worked and construct another larger model that goes across the entire classroom. 3 In this case, instead of tying off both ends, one end is tied off and the other end is routed through a pulley and tied off to some weights. 4 Once loaded, show that if weight is added or subtracted from the “anchor point” or a load from the cable, the system will move up and down as it reestablishes equilibrium. 5 A weight can also be hung from a pulley along the rope, like a ski gondola, demonstrating that an x-direction stabilizing force is required at all points along the rope except when the “gondola” is at the very center.

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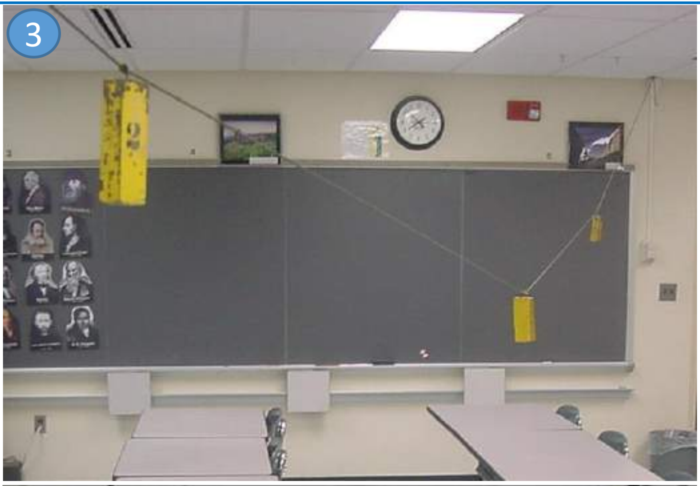

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5


FUN WITH FRICTION

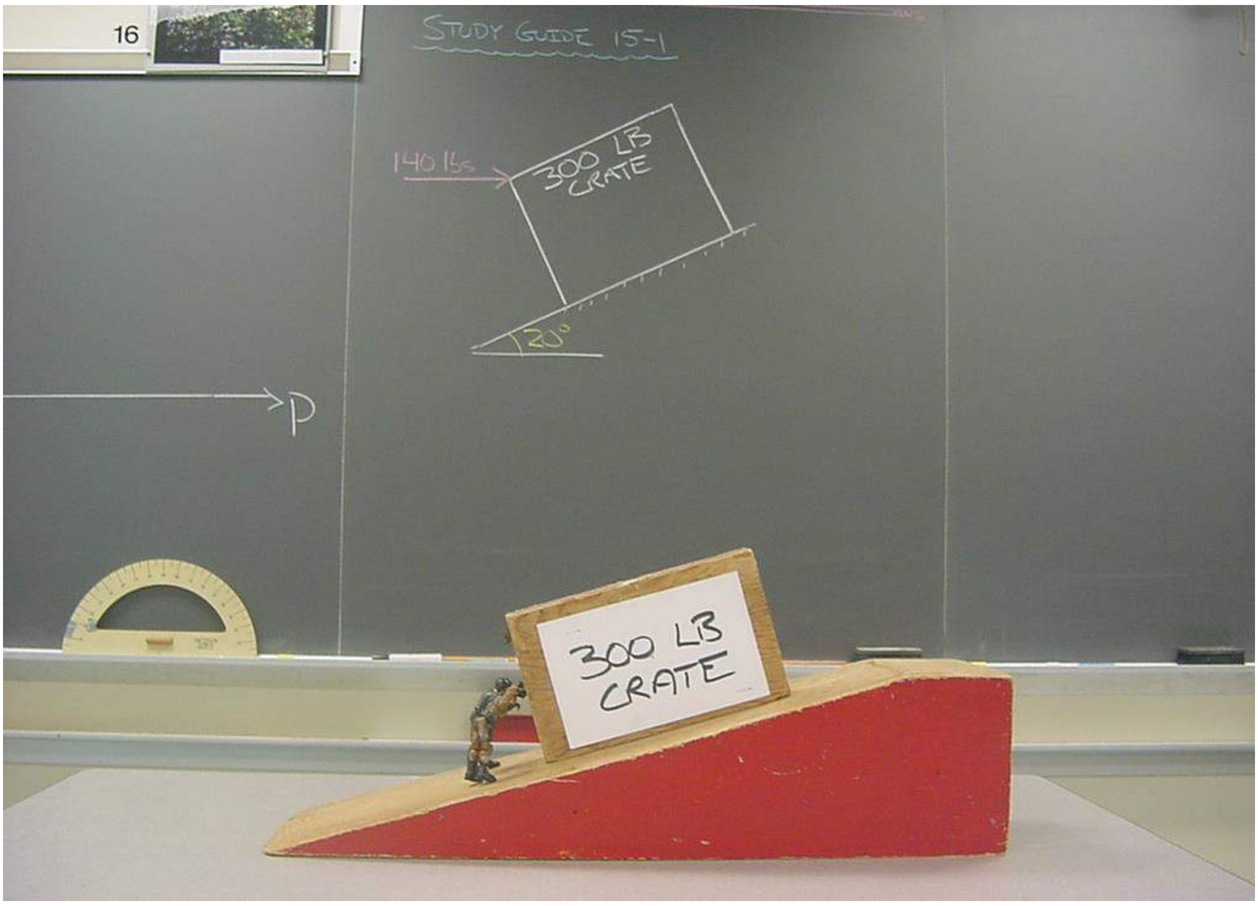
STATICS

Keywords: Coulomb Friction, Slipping, Tipping

Submitted by: John Richards and Tom Messervey

Model Description: Investigate slipping and tipping for Coulomb Friction. This demonstration should take 5-10 minutes.

Engineering Principle: These training aids provide a vehicle to discover the need to consideration three possibilities when investigating friction problems: 1) Nothing happens 2) Slipping occurs, 3) Tipping occurs.



REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Ramp	1	$10	A board or tilted desk could also work
Block	1	$10; 15 minutes	Two sides with sandpaper, two sides without
Chair / Cord / Student	1	$10	Used for the “Executioner’s Chair”

APPLICATION

Before Class: Prepare the box with sand paper.

In Class: Block with sandpaper: With the appropriate degree of inclination, the smooth side of the block will slip (lengthwise) and the rough side will not (with no applied force). Putting the block on edge, the smooth side of the block will slip and the rough side will tip with an applied force.

Executioner's Chair: Students always enjoy impending doom. With a chair and a cord, one can quickly bring out the teaching points of why it matters where the cord is attached to the chair, how the force of friction increases as the applied force increases, why it matters if tape is put on the floor, and the fact that tipping or slipping could occur. Intuitively, the students know the answer to all these questions, now one can discover the statics to support it.

Where to attach? Bottom – Ok.

He slides!

What is the cord is attached to the top? Still sliding!

Now there is tape on the floor. He tips!

AMAZING WEIGHT LOSS PROGRAM

STATICS

Keywords: Force Vector, Inclination, Shear

Submitted by: Tom Messervey and John Richards

Model Description: This is a simple and rapid demonstration of the perpendicular and parallel components of a force vector on an inclined plane. By weighing a student or instructor first on the floor and then at some inclination, a "loss of weight" is observed. This demonstration should take 5-8 minutes.

Engineering Principle: Spring scales are designed to measure the force acting perpendicular to their surface, and are deliberately insensitive to shear forces. Thus, the scale will read different weights for the same person if the inclination of the scale is changed. One can show the trigonometric relationship between the angle of inclination and the triangle formed by the weight vector and its components in as much detail as desired. If the angle of inclination is taken from the horizontal, the equations given hold true, and the "weight loss" is observed as the difference between the weight measured on a flat floor versus the normal component at the inclination.

$$w_{\perp} = w\cos(\theta) \qquad w_{||} = w\sin(\theta)$$

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Scale	1	$20	An old-style spring bathroom scale works best. Standard laboratory scales can also be utilized with a book instead of people if necessary.
Ramp	1	Varies depending on surface chosen	Any stable inclined surface.

APPLICATION

Before Class: Pre-position the title "Amazing weight loss program" somewhere in the classroom with the scale positioned nearby to get students curious.

In Class: To begin, have a student read off your weight while standing with the scale flat on the floor. 1 Then, place the scale on the ramp and have the student read your weight again. 2 Everyone will applaud your ingenious weight loss program. 3 Depending on your student population and how long the summer/winter break has been, students can struggle with how the angle of inclination relates to the triangle formed by the weight vector. Be ready to work through the derivation.

Additional Application: Prior to the scale demo, emphasize that statics is a subject in which you'll be touching, measuring, and investigating the world around you. As a warm up and trigonometry review, state that a sloppy design partner left one dimension off the ramp. Using only a protractor, challenge the student to find the missing dimension. Inevitably, students struggle with where to put the protractor and some need the refresher on basic trigonometry.

FRAME DEMOS

STATICS

Keywords: Force, Frame, Reaction

Submitted by: Jason Evers

<u>Model Description</u>: Introduce the concept of a frame and use a good free body diagram and the equations of equilibrium to solve for the forces and reactions acting on the frame. This demonstration should take 5-10 minutes.

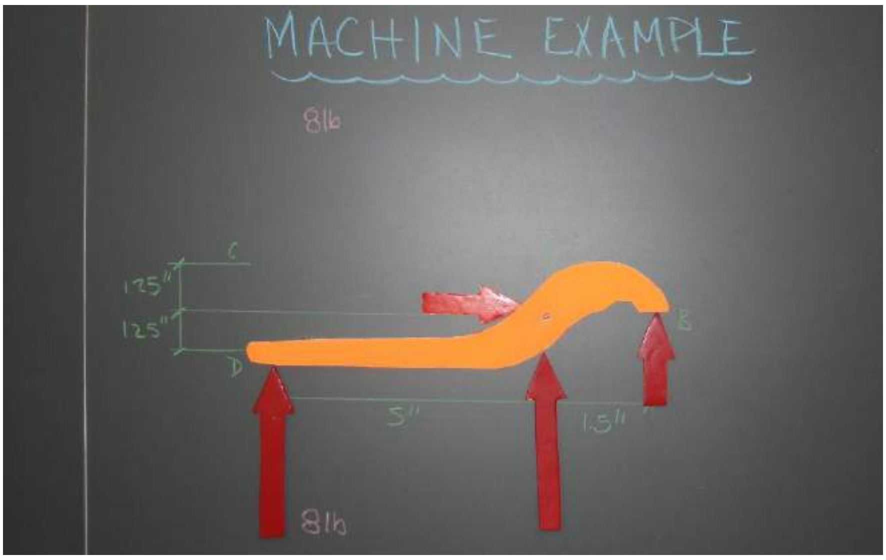
<u>Engineering Principle</u>: Frames and Machines are one way to classify a structure. As opposed to Trusses, Frames and Machines are comprised of at least one multi-force member. The difference between a Frame and Machine lies in the fact that a Machine uses moving parts to transmit forces and a Frame has no moving parts. Once you have introduced these definitions, it is good to show multiple examples of each interspersed with some that are not frames or machines. Bring as many examples to the class as you can find. Thereafter, talk about the techniques for solving for the forces acting on a frame comprised of members connected with frictionless pins (no moment transfer). This type of frame is used in order to be able to solve some simple structures and reinforce the concept. Introduce the concept of "pulling the pins" on this type of frame, drawing isolated free body diagrams of each of the members, and drawing in the equal and opposite pin reactions on each part of the free body diagram. If able, have several different Frames and Machines connected by pins that can be physically disassembled to use on the board or as hands-on physical models to hand around class. At this point we can solve for the forces acting on the structure using the equations of equilibrium on each of the member parts.

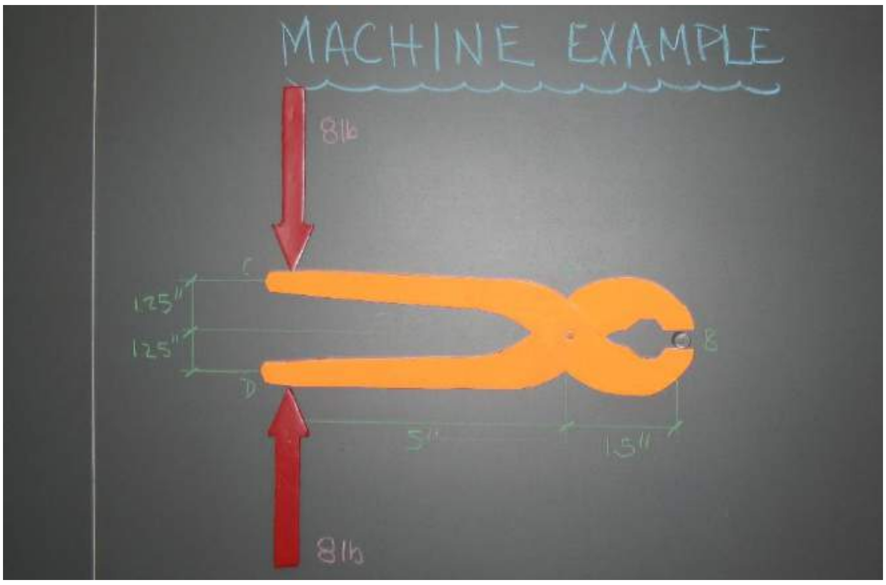
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Frames and Machines	As Many As You Want	Vary	Pick as many or few as you would like. There are very few restrictions.
Model of Pliers	1	$15; 30 minutes	The pliers model should be made of durable material and have magnets attached to its back so that It can be fixed to the board. It also should have the ability to be disassembled and isolated to solve for the pin forces.

APPLICATION

<u>In Class</u>: One of the simpler examples to demonstrate the concepts discussed above is a pair of pliers. It is fairly simple to build and one can usually find a few pairs of old pliers that could be disassembled to hand around the classroom. Start with the example on the board with the pliers together and ask the students to classify it. Then ask how we would determine the force acting on the bolt given this free body diagram. Since we could not, use our new technique of pulling the pins to determine all the forces acting on each of the members. Taking the pliers apart on the board simplifies the time required to draw a Free body diagram, but also leads to better understanding of the equal and opposite forces involved in the pin connections. Then look at one of the parts of the pliers and apply the equations of equilibrium to it and solve for the forces at the pin connection and at the bolt. After this example, more complex frames can be tackled with ease.





BELT FRICTION

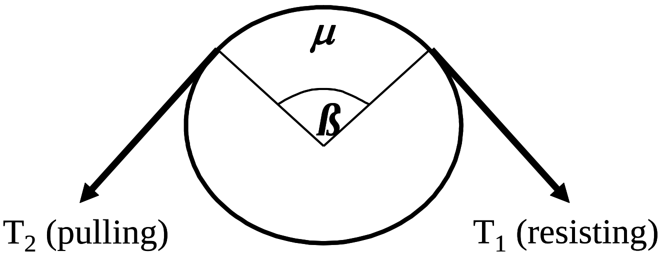
STATICS

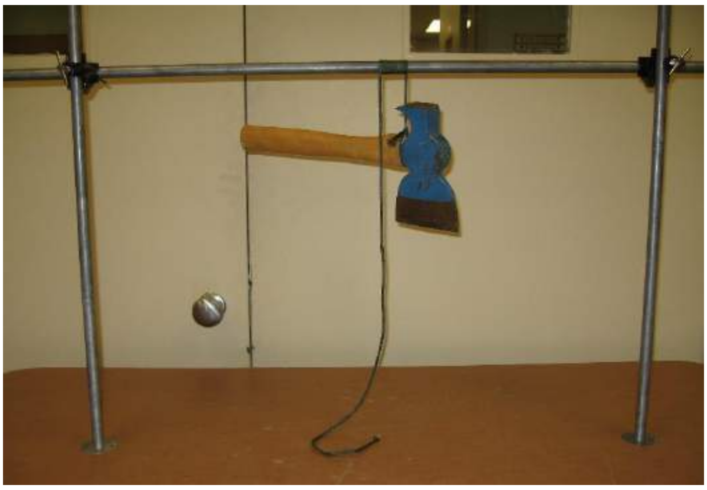
Keywords: Friction, Pulling, Resisting

Submitted by: John Richards

Model Description: Investigate belt friction. This demonstration should take 3-5 minutes.

Engineering Principle: These training aids provide a vehicle to discover the forces acting on a belt or rope when pulled over a fixed drum.
The basic equation for belt friction:





$$\frac{T_2}{T_1} = e^{\mu\beta}$$

where μ = coefficient of friction (either static or kinetic) and β = angle of surface contact between the belt and the drum (measured in radians).

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Object to suspend	1	$10; 3 minutes	The example uses a hatchet for dramatic effect, but any object that you can tie a rope to easily will work.
Rope	1	$5-10	Thin rope long enough to wrap around a pole enough times to hold the object stationary.
Fixed drum	1	$10; 20 minutes	Some type of drum to wrap the rope around

APPLICATION

Before Class: Prepare some type of fixed horizontal drum. The example uses a horizontal pole clamped to two vertical poles. Tie the rope to the object and wrap the rope around the drum tightly enough times to hold it stationary without tying it off. This shows that static coefficient of friction for that amount of angle of surface contact can hold the object pulling on the rope with just the resistance provided by the self-weight of the loose end of the rope.

In Class: Discuss why and how the supported object is suspended and not moving when the rope is not tied off at either end.

Additional Application: Start taking off wraps so that the object slowly starts to lower. Now the demo is using the kinetic coefficient of friction.

DISTRIBUTED STUDENT LOADING

STATICS

Keywords: Building Code, Distributed Load, Factor of Safety, Load Transfer, Loading

Submitted by: Jason Evers

Model Description: This model will get your students on their feet during class and help them visualize the concept of distributed loading. This demonstration should take 5-7 minutes.

Engineering Principle: In order to get students to begin to get a feel for load transfer and modeling loading, it is helpful to show an example. This exercise demonstrates the equation for a distributed load.

$$w = P/A \text{ (in units of lbf/ft}^2\text{)}$$

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Tape Measure	1	$15	This is used to measure the area the students will occupy.

APPLICATION

Before Class: None

In Class: The International Building Code (IBC) and other design codes specify various numbers for distributed loads for design. For students that are new to engineering classes, these numbers may appear a bit arbitrary. Show various codes and planning factors from textbooks for distributed loads and ask where these numbers might have come from. Answers will vary, but with proper questioning, we quickly can arrive at the above equation. Then, ask students how they would like to test the accuracy of the numbers in the code. Agree upon a fixed weight per student and multiply that by the number of students in the class and try to decide upon an area to divide by. This leads into some interesting discussions, but again with some guidance, students will get the fact that we want to consider the worst case, which is having the class try to get into as small an area as possible, which the instructor then measures. 1

CAUTION: You may have some students in class that are shy and don't enjoy being in extremely close proximity with others, so you can provide the guidance to occupy one tile square or get as close as possible without touching. Usually, the numbers calculated based on this exercise exceed the code recommendations by a large amount. At this point, discuss why the code factors are lower and talk about things like Factors of Safety on loading conditions.

PULLEYS: THE EQUILIBRIATOR CHALLENGE!

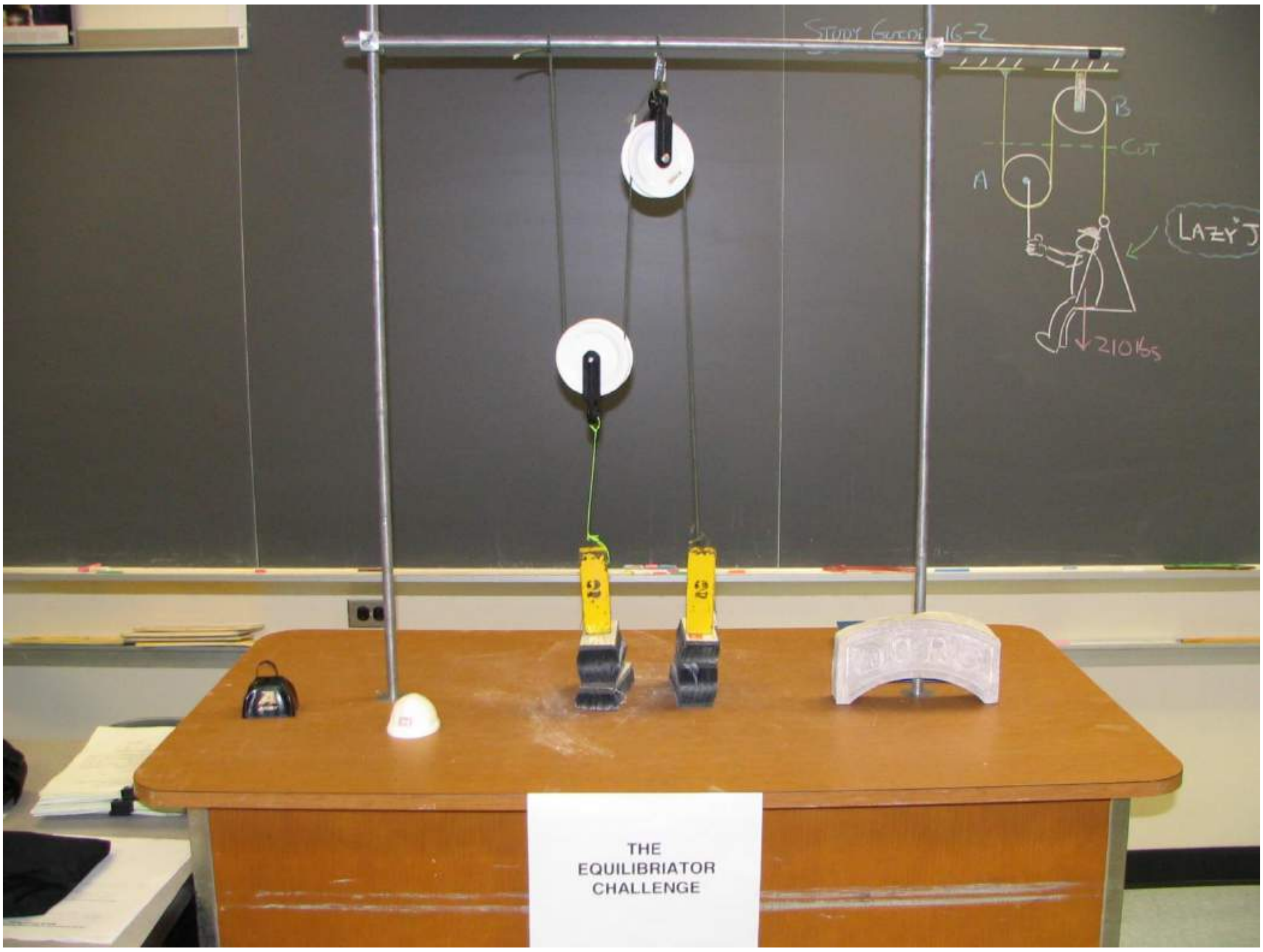
STATICS

Keywords: Mechanical Advantage, Pulley

Submitted by: Tom Messervey and Matt Morris

Model Description: This is a simple demonstration of the mechanical advantage associated with pulleys and a solution method for pulley problems. By building a pulley system in the classroom, students can gain a physical appreciation for the problem at hand. This demonstration should take 15-20 minutes.

Engineering Principle: This training aid demonstrates mechanical advantage obtained through pulleys and the fact that the tension throughout a continuous cable in a pulley system is constant.



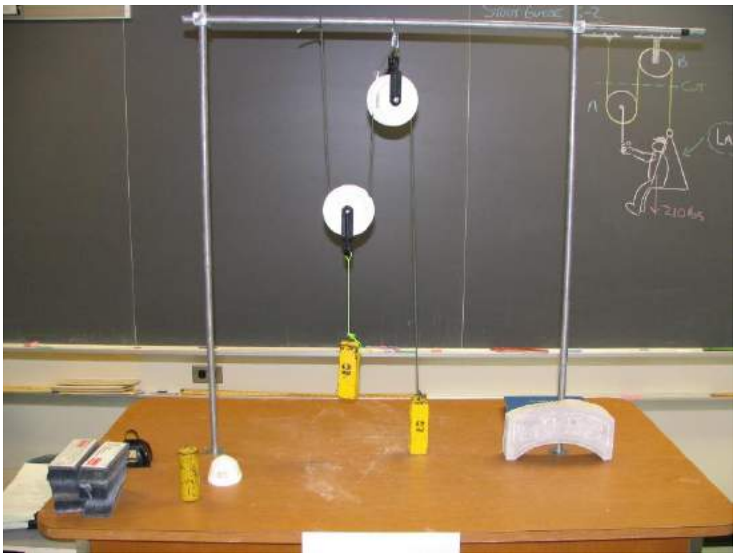
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Pulley	2	$10 each; 20 minutes	Any size pulley can work. They can also be suspended from the ceiling.
Cable	1	$5	Parachord works great
Weight	3	$8-10 each	Three 2 pound weights are pictured

APPLICATION

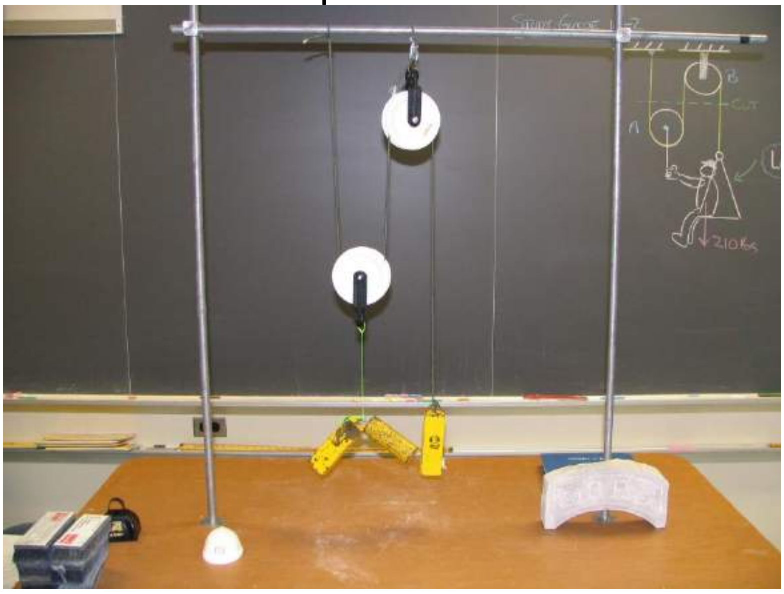
Before Class: Set up the pulley system as shown in the photo, with one pulley hung from overhead and the other "free" hanging in the system. Make sure the two weights are very similar, though they do not need to be exactly the same. Support both weights or you'll give away the conclusion.

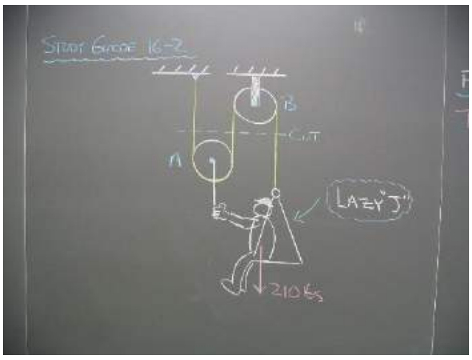
In Class: Class starts with the "Equilibriator Challenge." Have the students observe the system of pulleys and vote on which 2 lb weight will plummet to the desk when the erasers are removed. After some buildup, the erasers are quickly swept from under the pulley system and the weight on the right plummets.

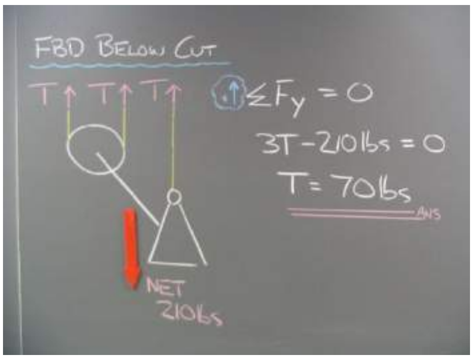


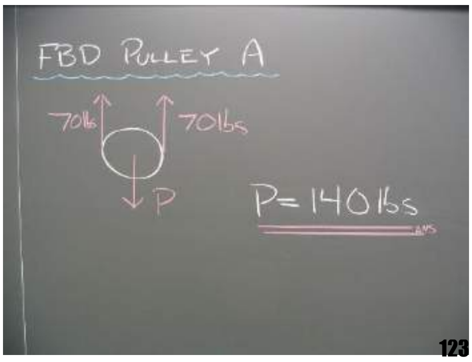
A Similar Example

We then develop how we could analyze such a system by investigating the problem of Lazy John, who wants to raise himself to inspect the roof (concerned with student safety) but doesn't have the strength to pull himself up without assistance. The students must compute how hard John has to pull to begin to raise himself using the pulley system. After solving the problem using appropriate diagrams (shown in the photos of blackboard solutions), students realize that the ratio between the forces to obtain equilibrium is 2-1. We then return to the physical model and validate that 4 lbs on the left and 2 lbs on the right remain static and are thus at equilibrium.









Additional Application: As students enter class, a clip from Monty Python's Holy Grail offers a great intro – the scene where it is proved that a certain woman is a witch because, using an equilibrium device, it is found that she weighs the same as a duck. This lesson is also one in which we begin discussing cable structures subjected to concentrated loads. Hence, we also utilize a pulley to balance one end of a cable system suspended across the classroom. By adding or removing weight from the counterweight, we cause the entire cable system to change shape to achieve a new state of equilibrium. A cable with three point loads is pictured first, and the counterweight is pictured second. The other end (without the counterweight) is just tied off to the ceiling.

THE TORQUE TESTER

STATICS

Keywords: Mechanical Advantage, Moment, Torque

Submitted by: Tom Messervey

Model Description: This training aid provides an example of what the students already know intuitively about mechanical advantage and applied moment. By using a dial torque wrench, units and physical measurement are readily observable and subject to discussion. This demonstration should take 5 minutes.

Engineering Principle: $M = F * d_{\perp}$

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Secure Bolt	1	$20; 20 minutes	Welded to a metal bracket or secured in a block of wood fastened to a desk. 1
Dial Torque Wrench	1	$150	If you have an automotive ME program, check to see if they have one to borrow. 2

APPLICATION

In Class: Start the class with the "Strongest Student Competition." The "Torque Tester" is the tool to judge the competition and the class elects the toughest member of the class. That person comes forward and is given the rule that his/her hand must be placed so that it touches the socket part of the torque wrench (decreasing their mechanical advantage). 3 After all, we don't want the strong student to flip the desk over through brute strength. A judge is selected from the class to read the dial on the torque wrench. A reading is obtained. The instructor then selects an obviously less strong member of the class. The second student is told that they have the freedom to grab the wrench anywhere they choose. 4 The strong student records the reading. Inevitably, the "weaker" cadet triumphs and the class enjoys a laugh.

LUG WRENCH VS. BREAKER BAR

STATICS

Keywords: Free Vector, Moment, Varignon's Theorem

Submitted by: Jason Evers

<u>Model Description</u>: Introduce Varignon's theorem to students as one way to determine the moment about a point. Show how moments are free vectors. This demonstration should take 10 minutes.

<u>Engineering Principle</u>: Varignon's Theorem states that the moment of a force is equal to the sum of the moments of that force's components about the same point.

$$M_{PT} = F_x + d\perp_y + F_y + d\perp_x$$

$d\perp$ = Perpendicular distance from the Force's Line of Action to the point.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Scale	1	$20	A typical bathroom scale will do.
Clamp	2	$8 each	Two heavier duty clamps that can hold down the bolt holder apparatus.
Bolt and Nut	1	$8	The head of the bolt should correspond approximately in size to a lug nut.
Bolt Holder	1	$25; 30 minutes	This device is simply meant to hold the bolt and be clamped to a desk or windowsill. It consists of a hollow shaft, large enough in inner diameter to allow the above bolt through, welded to two flat plates that will be clamped down.
Breaker Bar	1	$20	A breaker bar designed for lug nut applications is required; typically, any breaker bar from a car's spare tire assembly will work.
Lug Wrench	1	$12	Any type of lug wrench that has two equally spaced arms will do.

APPLICATION

In Class: Introduce the concept of Varignon's theorem in the context of changing a tire. The mounted nut is your lug nut on the tire. Using the breaker bar apply a moment to the nut, but push at an acute angle with respect to the longitudinal axis of the breaker bar. The definition of a moment included the perpendicular distance to the force's line of action. If the force is not applied perpendicular to the breaker bar as the nut is turned, then it is difficult to calculate the distance without extensive geometry. Introduce Varignon's Theorem to help at this point. Using the magnitude of the angle and the magnitude of the force applied to the breaker bar, calculate the moment. Choose these values carefully beforehand to prove the next point.

Contrast the Moment from a Couple with Moment from a Force
Calculate the Moment if using the lug wrench and the same total force magnitude as with the breaker bar. In this case though, the force is applied at two locations, so each hand applies ½ of the force. If the dimensions and forces are selected correctly, the Moment caused by the lug wrench will exceed that caused by the breaker bar.

Additional Application: *Show the Concept of Free Vector*
Demonstrate the concept of a free vector now by having a student stand on the scale and apply an upward force to the breaker bar. The student's weight should increase as long as the student keeps their lower body rigid. In contrast, when the same student applies an upward and downward force to the lug wrench, his/her weight should not change. This demonstrates the concept that there is no net force acting on the student. At this point, one can begin a discussion on the merits of each option and which might be better for the studs of the wheel.

MOMENTS AND COUPLES

STATICS

Keywords: Couple, Mechanical Advantage, Moment

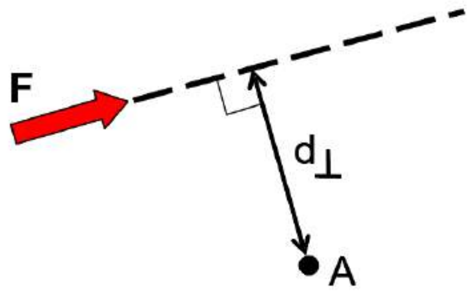
Submitted by: Jason Evers

Model Description: Introduce the concept of Moment and couples to your students by providing hands-on examples that they can relate to. Demonstrate how levers use the concept of moment to provide a mechanical advantage. This demonstration should take 5-10 minutes.

Engineering Principle: The Moment caused by a force about any point is defined by the equation below.

$$M_{PT} = F \times d \perp$$

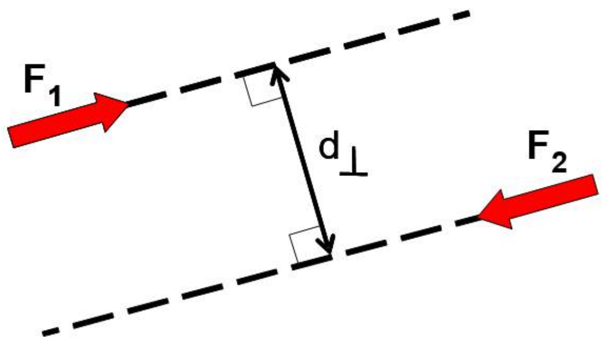
$d \perp$= Perpendicular distance from the Force's Line of Action to the point



A couple is defined as two forces, equal in magnitude, with parallel lines of action, but opposite in direction. The Moment caused by a couple is defined by the same equation, with the exception that the distance is defined differently and the Moment caused by a couple is a free vector that can be applied anywhere on the body.

$$M_{couple} = F \times d \perp$$

$d \perp$ = Perpendicular distance between the two Forces' Lines of Action



REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Tape Measure	1	$5	Any tape measure will do, but it must be long enough to measure the distance from a student's shoulder to their arm.
Barbell	1	$10-20	A barbell (or any object) of known weight.
Scale		$15	A typical bathroom scale will do, try to remain consistent in systems of units with the barbell weight and tape measure.

APPLICATION

In Class: A force's tendency to cause rotation is a scalar or vector quantity related to two things. Introduce what two things they are by asking a student to come up to the front of the classroom (try to choose a student that is fairly athletic). Tell them that the class will calculate the moment caused by a textbook (or some object lighter than the barbell) about the students shoulder. Give the student the book and ask them which causes greater rotation about their shoulder, holding it close to their body, or holding it far away. The students will answer correctly. Then add the first part of the equation defining moment on the board ($d \perp$). (You can also show why the perpendicular distance is the important dimension here). Then, ask the same student whether they would like to hold the book far away or the barbell and give them the barbell and ask them to hold it out. The students will answer correctly, then add the second part of the moment equation to the board (F). Next, measure the student's arm length from the shoulder with the tape measure and calculate the moment on the spot. (Make sure to have the student continue to hold the weight while doing so.)

Additional Application: Demonstrate how Levers use the concept of Moment to their advantage. You can put the Archimedes quote "GIVE ME A PLACE TO STAND AND I WILL MOVE THE EARTH" on the board and ask for students to guess who said it. Then, proceed into different types of levers that are seen in everyday life and how they have defined a way to determine the weights and forces that make these levers work.

THE PERSUADER

STATICS

Keywords: 3-D, Equilibrium, Force, Magnitude, Moment, Vector

Submitted by: Jason Evers

Model Description: Use this daunting looking model to set the stage for a lesson on 3-D equilibrium and eventually persuade your students that it's easier than it looks! This demonstration should take 20 minutes.

Engineering Principle: 3-D equilibrium for a non-concurrent force system requires the simultaneous solution of six equations of equilibrium, three equations for summing forces and three equations for summing moments about each axis.

$$\sum F_x = 0; \sum F_y = 0; \sum F_z = 0$$

$$\sum M_x = 0; \sum M_y = 0; \sum M_z = 0$$

In order to keep all of these equations and forces organized, it becomes important to begin to describe forces and moments with Cartesian vectors and to use matrix algebra to solve the systems of equations that result from application of the principle of equilibrium. For Example, the Moment and Force Reactions at a fixed support might be described as:

$$M_R = \{A_i + B_j + C_k\}$$
$$F_R = \{D_i + E_j + F_k\}$$

Some supports will not hinder translation in or rotation about one or more axis. In this case, the value for the magnitude given by A-F above will be zero. In order to describe a force as a vector given the force's magnitude and line of action, one must first determine the unit vector of the force, then multiply it by the force's magnitude. For example, the Unit vector describing a force with a line of action from point A to point B is found by dividing the position vector from A to B by the magnitude of that vector.

$$\widehat{U}_{AB} = \frac{AB}{|AB|}$$

Once the unit vector is found, the Force vector can be calculated by multiplying the unit vector by the force magnitude, which is f in this case.

$$F_{AB} = |f| \times \widehat{U}_{AB}$$

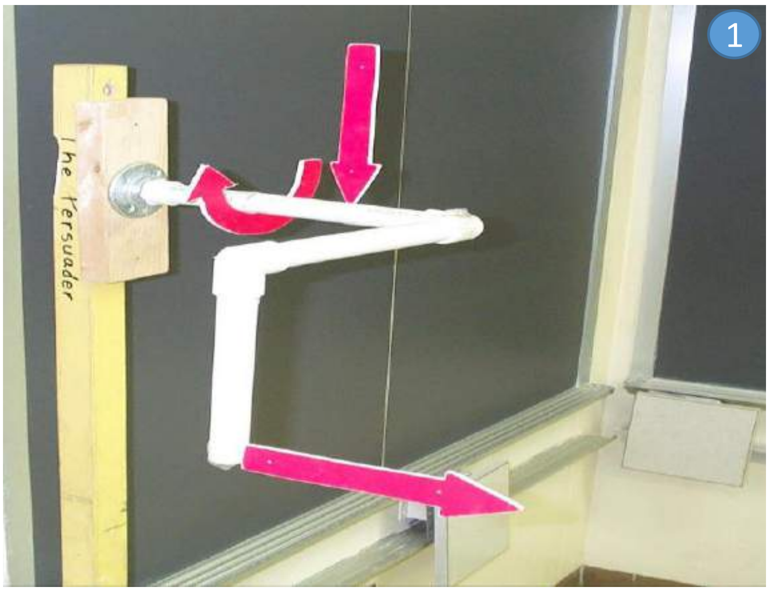
The final key element to determining equilibrium in 3D is to determine the Moment vector that is caused by any force vector acting at a distance from a point. In order to determine this, the cross product is used between the position vector from the point in question to any point along the force's line of action and the Force vector. Using our previous example, the Moment caused by our Force AB about point 0 would be given by the cross product of a position vector from point 0 to any point along the force's line of action (in this case we chose point A) and the Force vector AB.

$$M_0 = r_{0A} \times F_{AB}$$

Armed with these basics, 3D equilibrium problems can be easily solved.

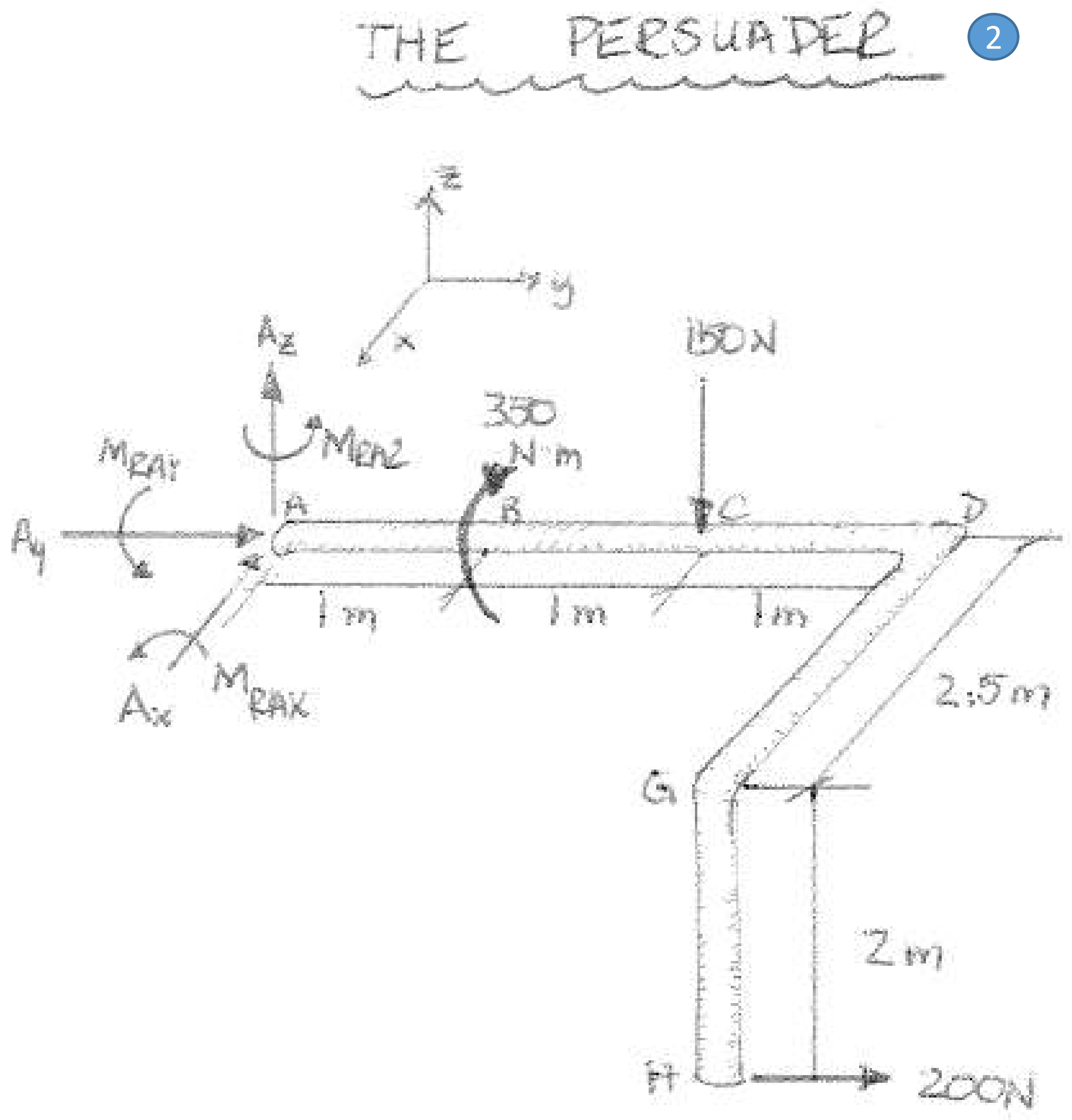
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Force Vector	2	$5 each; 25 minutes	Each Vector represents one force acting on the PVC pipe system
Moment Vector	1	$5; 15 minutes	This vector represents a moment acting on the PVC pipe system.
¾ " PVC Pipe	75 cm	$5; 10 minutes	The scale of this model is 1:10. The pipe should be cut into 3 pieces of 20cm, 25cm, and 30cm.
¾" 90° PVC Pipe elbow	2	$0.25	
¾" threaded PVC Pipe end	1	$1	
Threaded Pipe Mount	1	$8	This section mounts to the 2"x 4" base with screws and holds the threaded PVC pipe end.
2" x 4"	25 cm	$5; 5 minutes	This is the base of the persuader that can be mounted to a wall or door with a few clamps.
2" Nail	3	$3	These nails will hold the force and moment vectors to the model.
¾" Screw	4	$3	These screws mount the pipe mount to the 2"x 4" base piece.



APPLICATION

Before Class: Build the Demonstrator. (1) Refer to the Free Body Diagram (2) for assistance when building the demonstrator. Mount the threaded pipe mount to the center of the 2"x 4" section. Thread the PVC pipe end piece into the pipe mount. Connect the 30 cm section of pipe to the threaded end piece. Place a 90° elbow on the opposite end of the 30 cm section. Connect the 25 cm section of pipe to the 90° elbow. Place another 90° elbow on the opposite end of the 25 cm section. The final 20 cm pipe section should then connect to the elbow. Drill holes through the pipe at the locations for each of the externally applied forces and moments. These holes should be large enough to pass one of the 2" nails through. The nails should be glued down and hold the force and moment vectors to the apparatus. One additional step that can be helpful is to label the points and distances on the Persuader with either permanent marker or by taping small pieces of paper to it.



In Class: At the beginning of class, point out the persuader and really build it up as a very difficult problem to solve, but that by the end of class it will be one that they can solve with ease. Begin by defining a Cartesian vector in 3 dimensions and what it means. Then, discuss support conditions in 3 dimensions and what vector support reactions would result from a fixed, hinge, cable, and other types of supports. Next, review how to describe a force with a certain line of action and magnitude by a Cartesian vector. First, determine the position vector for the line of action, then calculate the unit vector by dividing the position vector by its' magnitude. Finally, multiply the magnitude of the force by the unit vector to get the Cartesian force vector. The final step prior to being able to solve "the Persuader" is to review the procedure for calculating the moment of a force about a point in 3D space by using the cross product.

Translate the Persuader into a free body diagram on the board by isolating the body and replacing the support with the respective reactions that would occur. The free body diagram should look like the picture shown above 2 when completed.

Once that is complete, the process of writing all of the force vectors and position vectors, then applying the equations of equilibrium is really quite painless. Show the students how to organize their equations into a table or a matrix in order to keep all of the unknowns straight in the equations.

VARIGNON'S I-BEAM

STATICS

Keywords: Force, Line of Action, Moment

Submitted by: Jason Evers

Model Description: Introduce Varignon's theorem to students as a simple way to determine the moment about a point. This demonstration should take 5-7 minutes.

Engineering Principle: Varignon's Theorem states that the moment of a force is equal to the sum of the moments of that force's components about the same point.

$$M_{PT} = F_x \times d_{\perp y} \times F_y \times d_{\perp x}$$

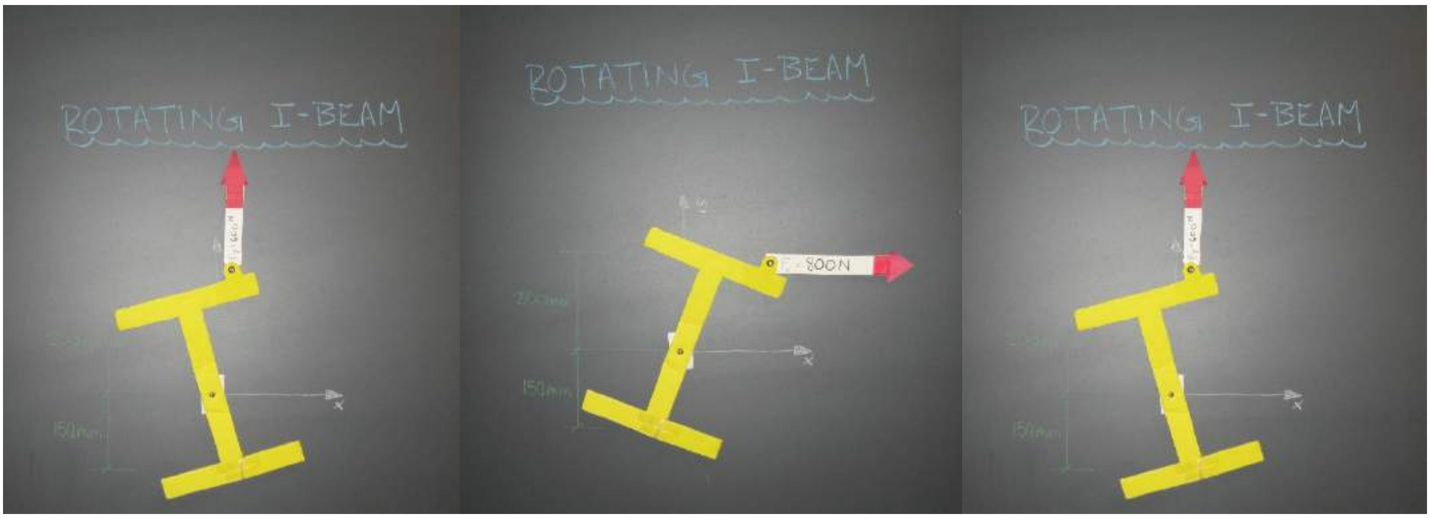
$d_{\perp}$ = Perpendicular distance from the Force's Line of Action to the point

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Force Vectors	3	$15	One vector represents the total Force Vector. The other two should be smaller and represent the components of the force in each orthogonal direction. The force vectors should have magnets taped to their backs.
I-Beam	1	$10	The I-Beam should be made of durable material, then fastened to another piece of poster board with a light, large headed bolt. This allows the I-beam to rotate when fixed to the board.

APPLICATION

In Class: Introduce the problem of determining how much moment this force acting on a lifting eyelet on an I-beam will cause about the point O. Show how the complex geometry can complicate this calculation. Now Introduce Varignon's theorem as a simple way to avoid this problem. After stating the theorem, put it into practice on the I-beam. Break the force into it's orthogonal components. After doing so calculate the combined moment of the force's components about point O. Show how each component can cause either positive or negative moment, so students must pay attention to the direction that each force causes rotation in.



K'NEX TRUSSES

STATICS

Keywords: Stiffness, Strength, Truss

Submitted by: Ronald Welch

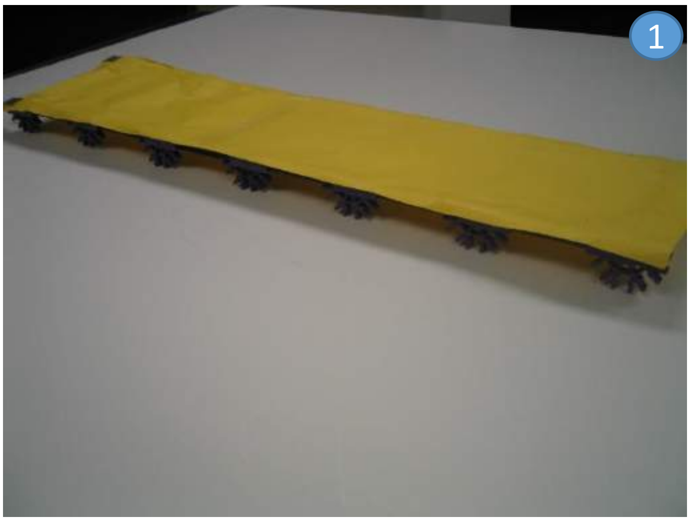
Model Description: This simple pair of K'NEX models can demonstrate how trusses greatly increase the strength/stiffness of structures without adding much weight. The trusses are built out of K'NEX pieces and topped with construction paper to produce a roadway. Text books are used to load the trusses to demonstrate its strength to weight ratio. This demonstration should take 15 minutes.

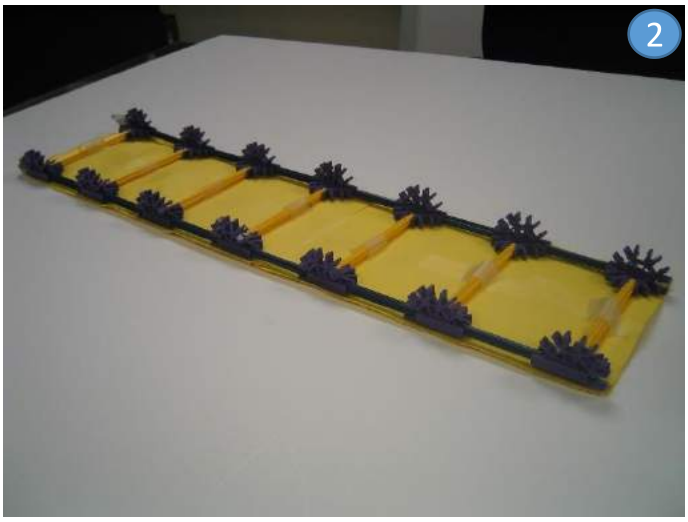
Engineering Principle: The basic equations required for analysis are the equations of equilibrium and trigonometry. However, no real numerical analysis is required beyond measuring the weight. The model is used primarily for developing a feel for the importance of trusses as a structure, especially when considering the structure weight to load carried ratio, and that the weight of the truss can be initially ignored during the design (add weight of truss members back in during the final design checks).

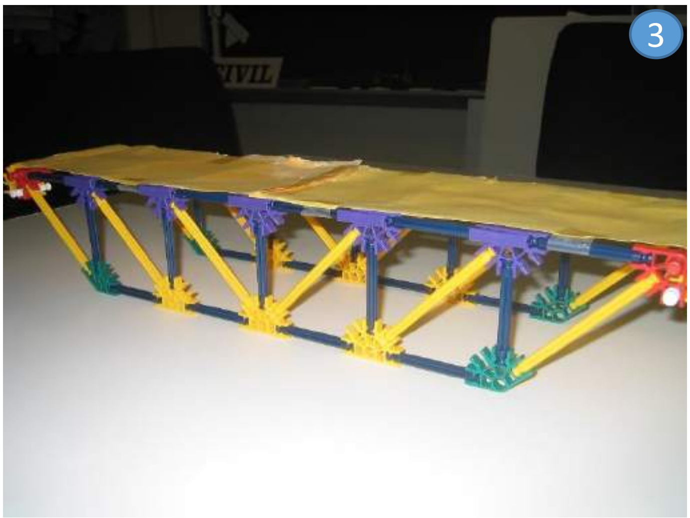
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
K'NEX Pieces	Lots!	$300 (for set referenced); 30-45 minutes	These pieces are connected into a number of triangle shapes to form 2D and then 3D trusses with supports. The connection of the 2D trusses forms a rudimentary "road" for the bridge. Also, a so-called "road" without trusses is made to demonstrate how flexible a bridge can be without trusses (long members overly dramatized for effect). All of the K'NEX pieces shown are part to the Big Ball Factory set. Individual pieces can be purchased to build your own kit. For the bridges in 1 2 3 , you will need: Bridge without trusses - 7 yellow (3.25 inches) straight pieces, 12 blue (2.125 inches) straight pieces, 28 purple connectors (2 each forming a joint); Bridge with trusses - 17 yellow (3.25 inches) straight pieces, 30 blue (2.125 inches) straight pieces, 2 red (5.125 inches) straight pieces, 4 white (1.25 inches) straight pieces, 20 purple connectors (2 each forming a joint), 4 green connectors, 14 yellow connectors (2 each forming 4 supports), 2 red connectors.
Load (textbooks)	Any		Test how many textbooks is safe for the K'NEX truss model so as to not actually break the connections, but make sure the number of books is effective in making a point about the strength of the bridge.

Item	Qty	Cost and Build Time	Description/Details
Construction Paper	2	$1; 5 minutes	Two pieces of construction paper make the roads for the two bridges.
Tape	1	$2	Tape is used to attach the paper to the two bridges.
Supports	2		Supports are needed to hold the ends of the bridges off of the desk while they are being loaded. Anything can be used for this: more textbooks for example.
Scale	1	$15	A scale is used to weigh the truss and the load it is able to carry successfully. No scale is really required. A student can provide a qualitative answer by placing the truss in one hand and the load carried in the other hand.







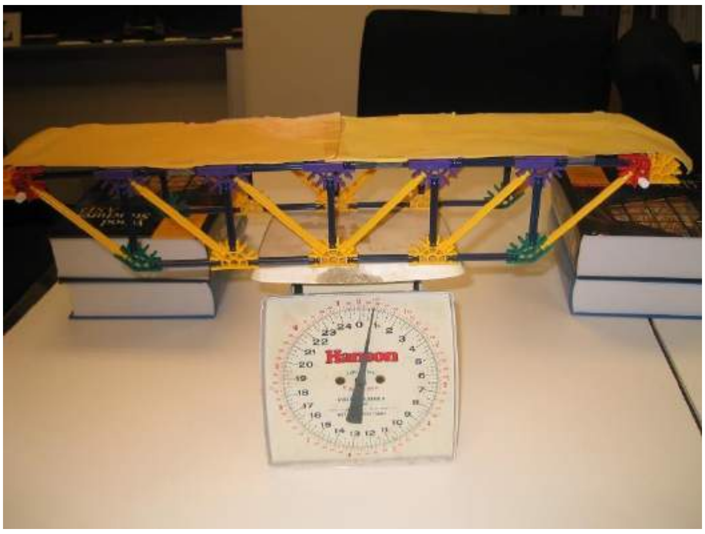
APPLICATION

<u>**Before Class**</u>: Construct the bridges out of K'NEX and load test the truss bridge to make sure you don't overload it and break it during class (normally only connections come apart, but occasionally, the textbooks can cause a connector to occasionally break a small piece off), especially if teaching multiple sections of the same lesson.

In Class: Show the class the bridge without trusses. Place it in the hands of a student and ask how much it weighs (qualitatively). Place it on the supports and place a light object on it and show how it begins to deflect under the load. Ask the student to compare the weight of the structure and the load placed on it (qualitatively). Show the students that it is bending and ask why it isn't very strong. Generally long slender members acting as simply supported members are not efficient in supporting loads over long spans. How can we make the structure stronger – greater depth to the members (Draw on their experience of building a tree house using 2x4 members. The member is stronger when loaded perpendicular to the greatest depth – use a ruler to demonstrate)? How can we get greater depth without too much more weight? If and when you can elicit a statement about trusses from the class, bring out the other bridge.

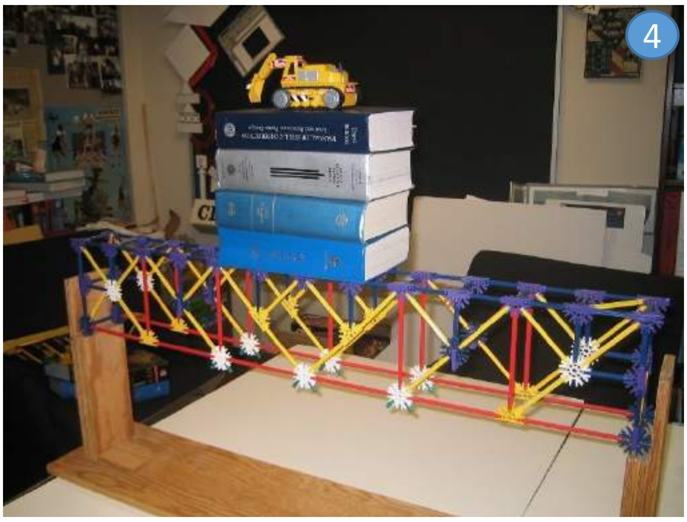
Ask the same student how much it weighs compared to the first non-truss bridge (not much more…). Set the bridge with trusses on the supports and place the same small object on it. Lead the class to see how much more load it can support. Begin to load textbooks on the bridge (can use some of the students' texts).

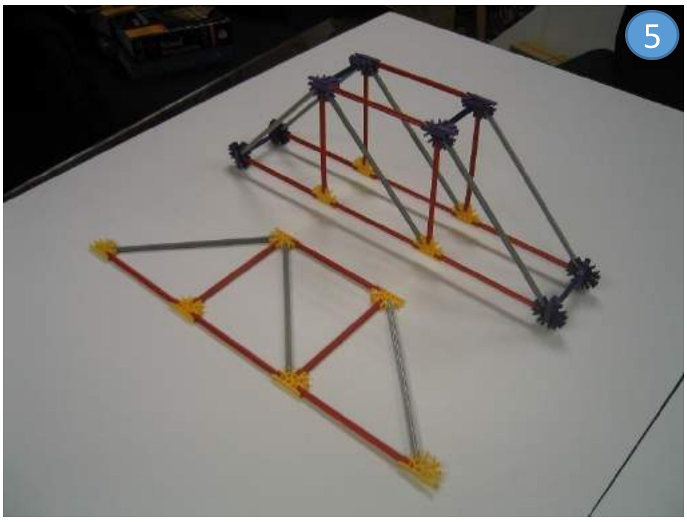
Weight the bridge, then the textbooks. There should be quite a significant difference in ratio between the weights. A light truss structure can support a load that is many times greater than the weight of the actual structural members over long spans.



<u>Additional Application</u>: Before loading the truss bridge, ask a student how much it weighs by placing the bridge into his/her hand. Then ask how much load the bridge might be able to support? Once the students see how much stronger the bridge with trusses is as compared to the one without trusses, call one of the students up to the front of the class. Give the student the two bridges to hold and ask if there is much significant difference in weight. Then take away the bridge without trusses and begin to stack the textbooks that had been loaded on the second bridge onto the student's hand until all are there of he/she cannot hold any more (drama and fun!). Then bring out a scale to show numerically how different the weight of the bridge is when compared to the weight of the load.

More elaborate truss structures/supports that represent real bridges can be developed for this same demonstration. This bridge is an approximate example of the Falls Bridge over the Schuylkill River Philadelphia, PA. 4





Building a 2D K'NEX section 5 of a 3D K'NEX truss allows for a discussion of actual analysis of 3D structures. The 3D bridge structure is mentally taken apart into two 2D sections with one-half of the deck load (for this case) placed on each half. The engineer then draws a Free Body diagram (FBD) of the 2D section and completes the analysis to determine the loads in each member. This K'NEX model matches the planned in class truss analysis problem using both the Method of Joints and Method of Sections.

A discussion can ensue concerning other portions/assumptions of the definition of a truss: a structure composed of slender members joined together at end points by frictionless pins; loads only applied at joints; all truss members are 2-force members; and member weight is negligible. Slender members is obvious, but showing connections using K'NEX pieces leads to discussion/review of a previous topic – concurrent force systems and frictionless pins of years gone by. The fact that truss members are 2-force members will be shown during analysis using Method of Joints and Sections. The load (books) not totally going through the joints leads to a possible discussion that truss members are not always only 2-force members (if the class has been prompted to know the difference between the current theory and what real structures experience and adjustments to analysis at later times). Usually, the deck will carry the load to the joints. Member weight is generally negligible – readily apparent by the initial demonstration.

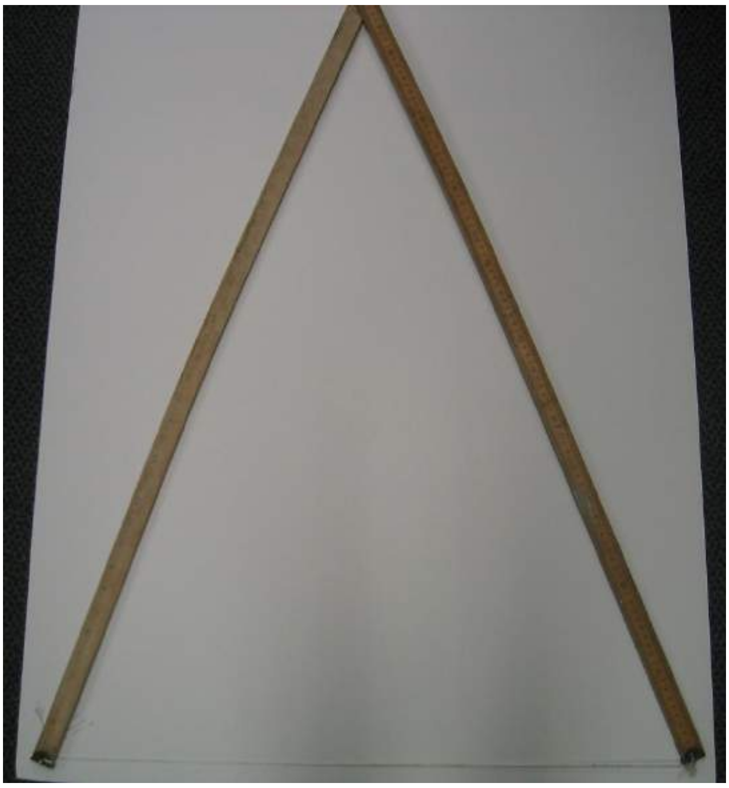
RULER TRUSS

STATICS

Keywords: Truss

Submitted by: Ronald Welch

Model Description: This demonstration shows the simplicity of a truss. The equipment consists of a single triangle made of two rulers and string - forming a truss. The truss is held on two desks by students and given a load by another student. This shows the innate strength of the simple triangular shape used in trusses. This demonstration should take 5-10 minutes.



Engineering Principle: The basic equations required for analysis are the equations of equilibrium and trigonometry. However, no real numerical analysis is required beyond measuring the load applied if scales are placed under each leg of the Ruler Truss (not shown). The model is used primarily for developing a feel for the importance of triangles as a structure, especially when considering truss stability.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Yardstick	2	\$5 each; 15 minutes	The yardsticks will be attached at one end with a bolt and a nut so that they can rotate freely. They will be attached at the other end by a string that is about 30 inches long so that the three parts form a triangle.
Bolt	1	\$3	The bolt (2 inch x ¼ inch) will be used to connect one end of the yardsticks.
Nut	1	\$1	The nut (1/4 diameter) will be used to secure the two yardsticks in place forming a generally frictionless pin.
String	30 inches	\$5	The string will be attached to the far end of the yardsticks to create a triangular truss.

APPLICATION

Before Class: Set up the ruler truss with the 2 rulers, bolt, nut, and string.

In Class: Set up the rulers and string on two desks and assign two students to hold the bottoms of the rulers using only their thumb and index finger (ruler weight actually resting on the desks) without the string being taut. The students are only trying to keep the structure vertical.

Ask another student to apply a force to the top of the rulers. The students holding the bottom using only their fingers should not be able to resist the outward movement of the rulers as the student presses down. Based on the loading applied, ask the students what type of load is in each leg of their simple truss? Pull from the students that the rulers are in compression while the string is in tension.

Additional Application: A discussion can ensue concerning the definition of a truss: a structure composed of slender members joined together at end points by frictionless pins; loads only applied at joints; all real truss members are 2-force members; and member weight is negligible. Slender members and frictionless pins are obvious, but the fact that truss members are 2-force members jumps out with this simple model. Additionally, vertical stability becomes an issue that the two students holding the bottom can address by how hard it is to keep the structure vertical if the other student does not load vertically. How do we keep a truss from falling over? Can we ensure loads are only vertical? Etc.?

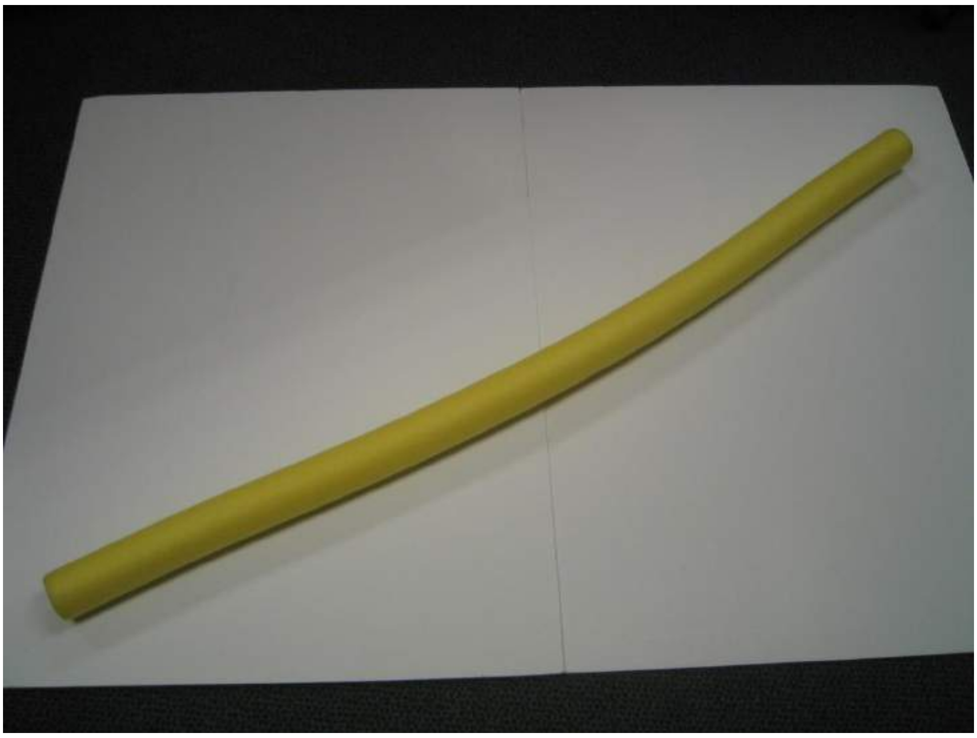
WACKY FUN NOODLE

STATICS

Keywords: Axial, Compression, Tension

Submitted by: Ronald Welch

Model Description: This is a simple demonstration to show how tension and compression affect members of trusses. A wacky fun noodle (tube floatation device) will be used to demonstrate the effects of tension and compression on axial members. Students pull or push each end to display the desired behavior. This demonstration should take 5-10 minutes.



Engineering Principle: In Mechanics of Materials, the concept and theory of buckling can be demonstrated using the wacky fun noodle.

$$P = \frac{\pi^2 EI}{(KL)^2}$$

In statics, the wacky fun noodle can quickly demonstrate that a structural member made of the same material can behave differently and have different strengths during tension and compression (trusses). The demonstration can link the current content to content to be presented in Mechanics of Materials (linking courses).

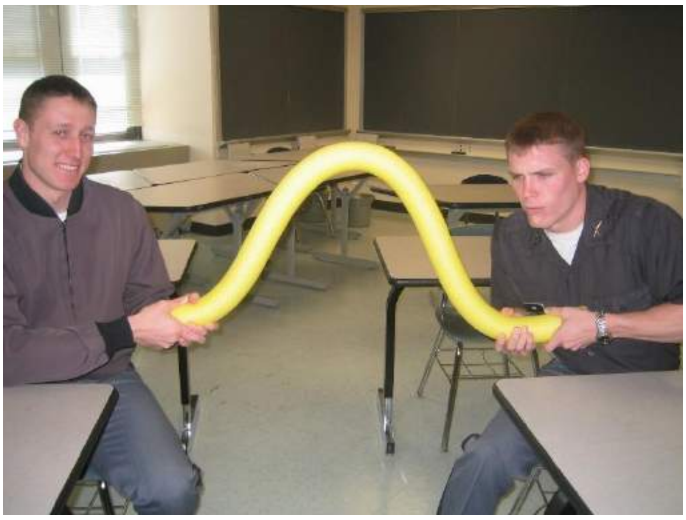
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Wacky Fun Noodle	1	$3-5	These are foam floatation devices that are many different sizes. The one used here is about 57 inches long (shorter members of 24 inches also work).

APPLICATION

Before Class: Buy a Wacky Fun Noodle.

<u>In Class</u>: Ask two students of the class to each grab an end of the fun noodle. Have them pull on it first to demonstrate tension. Have them estimate the load they are able to put into the effort (qualitatively). Then have them push on either end, and show that it buckles and bends outward. Have them estimate how much load is required to buckle the wacky fun noodle. Through active discussion, pull out of the students that materials used for truss members generally can support much larger tension loads in comparison with compression loads. Ask the question, since our truss members are 2 force members (tension or compression), is it important to know whether the load the member will support is a tension or compression force? Of course it is since compression forces can cause buckling which could lead to catastrophic failure of the member and possibly the entire truss.

Ask the class what would happen if the length of the noodle where the force is being applied is decreased. Demonstrate, by asking the students to sit closer together as they apply force to the noodle (length decreased), that the effects of tension do not change but the compressive force needed to make it buckle is much greater.


Demonstrate compressive forces acting on the noodle by standing the noodle vertically on a desk. Ask one student to sit in a chair and hold the bottom of the wacky fun noodle and another to stand and push vertically on the top of the noodle so that it buckles. It should buckle in the shape of a C.

Ask another student to hold the noodle loosely in the middle (like a sleeve connection) and ask the students what they think will happen when force is applied to the top. Have the student apply a force vertically to demonstrate to the class that the noodle makes an S-shape because of the constraint in the middle. Ask the student applying the load if more load was required? The answer is yes and theory in Mechanics of Materials will show 4 times as much load is required. K is the factor that takes into account that the length is different based on end conditions. Assuming the end conditions are simply supported and a support is placed at mid-length (i.e., the length becomes L/2), we can see in the equation that the ½ is squared and inverted to estimate 4 times the load required to cause buckling.

Additional Application: If the student applying the load cannot feel the need for 4 times the load to cause buckling with another student holding the middle, then repeat the two previous steps with a shorter length of the noodle being acted upon. The student applying the force should be able to feel that much more force is needed to make the noodle buckle (four times the amount of force), and the class can once again see the S-shape formed when another student holds the middle of the length of noodle.

With vertical lines drawn along the length and horizontal lines drawn circumferential, torsional behavior can be displayed using the wacky fun noodle. A circular shape when twisted is experiencing pure shear and the squares created by drawing lines on the surface do not change size (area), but change shape (square becomes a rhombus – see rubber shapes physical models).

The wacky fun noodle can be used as a general flexural member as well. The lines draw circumferentially will generally remain straight as the noodle is bent slightly due to flexure – demonstrating plane sections remain plane (see foam beams physical models).

When applying a bending moment, the students can see the top is in compression and the bottom in tension if applying a positive moment.

WOODEN TRUSS 2D

STATICS

Keywords: Stability, Strength, Truss

Submitted by: Ronald Welch

Model Description: This is a simple demonstration to introduce the basic principles of truss behavior and analysis. It will show how the shape of a truss—and not necessarily its weight/material—determines its stability. A simple truss design will be used to show that triangles are the important stability shape used in trusses rather than squares or rectangles. This demonstration should take 15-20 minutes.

Engineering Principle: The basic equations required for analysis are the equations of equilibrium and trigonometry. However, no real numerical analysis is required. The model is used primarily for developing a feel for the basic definition for a truss: a structure composed of slender members joined together at end points by frictionless pins; loads only applied at joints; all truss members are 2-force members; and member weight is negligible.

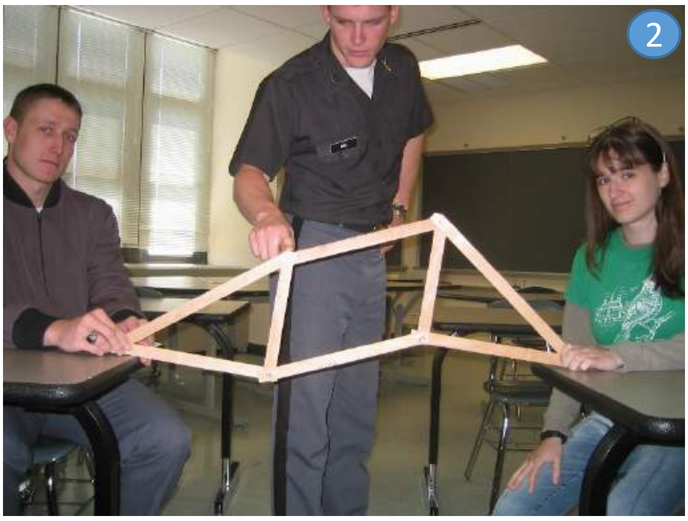
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Pieces of Wood	9	$45; 1 hour	Any wood type can be used to include scrap pieces from a previous project! In the picture provided, each piece is an inch wide and about a quarter of an inch thick. Each piece needs one hole drilled in each end so that they all can be connected with nuts and bolts. Pieced together, they make a truss with 4 triangles, with the two middle triangles able to be combined into a square by removing the diagonal member. 4 pieces (members) need holes 12 inches apart. 3 pieces (members) need holes 15 inches apart. 2 pieces (members) need holes 9 inches apart. Holes are slightly larger than 3/8 inch for this example.
Bolts	6	$15	4 bolts need to be 1.5 inches long x 3/8 inch and the other two can be 1 inch long x 3/8 inch. Diameters other that 3/8 inch can be used – just ensure the holes and bolt diameters match.
Nuts	6	$10	Nut diameter to match the bolts. The 6 bolts connect 8 of the 9 members in place, but are screwed finger tight so that they all can move relatively freely (pinned connection). The middle diagonal member is just placed on the ends of the longer bolts after the nuts are screwed on for easy removal.

APPLICATION

Before Class: Construct the truss out of the eight members and six nuts/bolts. Be certain that the joints are finger tight to move freely when the diagonal member is not in place.

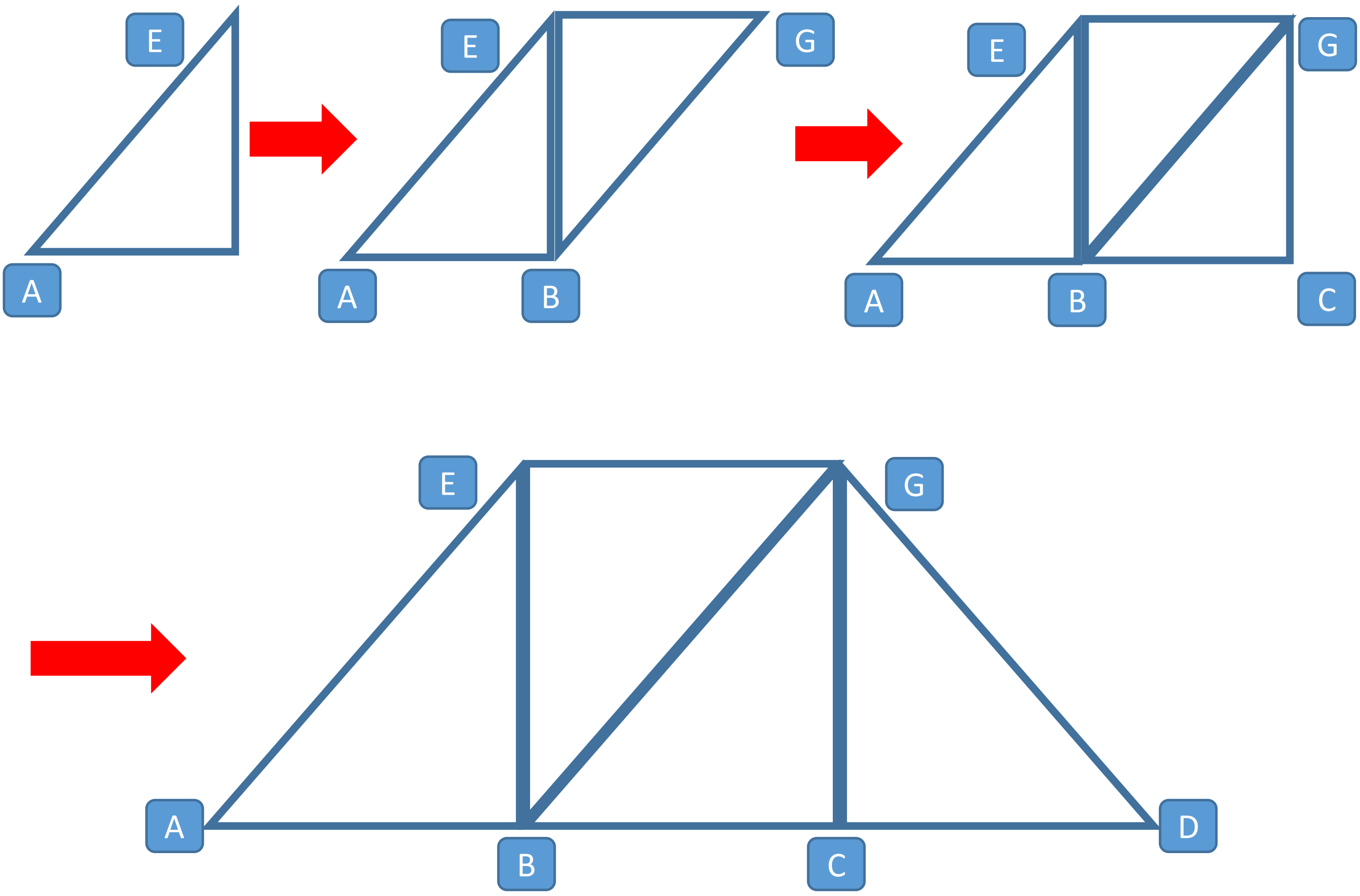
In Class: Through questioning of the students define a truss: a figure consisting of straight, slender members connected at joints by frictionless pins. Show the class the truss without the center diagonal member and give it to two students to hold between two desks so that it doesn't look unstable. 1 Have a third student apply force to one of the top two joints, making the figure easily fail. 2 Ask the students what they think the problem is with the truss. Try tightening the bolts even further with your fingers to see if that is the problem. Once the correct answer is given – the truss members must form triangular shapes when connected, correct the truss by placing the diagonal member on the bolts (so that is what this extra member is for…!).



Demonstrate how much stronger this design is by having the same student push on each of the top joints while the other two are holding it. 3 Ask the student to describe quantitatively how much stronger/stable the truss is with the diagonal member in place. 4

Additional Application: A discussion can now ensue concerning each of the portions/assumptions of the definition of a truss: a structure composed of slender members joined together at end points by frictionless pins; loads only applied at joints; all truss members are 2-force members; and member weight is negligible. Slender members is obvious and the bolts finger tight allow for the possibility of frictionless pins, but showing connections of real joints with gusset plates leads to discussion/review of a previous topic – concurrent force systems and frictionless pins of years gone by. Truss members are 2-force members will be shown during analysis using Method of Joints and Method of Sections. The student applying the load will be able to quantitatively compare the weight of the wooden truss to the load he/she is placing at the top joints – member weight is generally negligible, as well as leading to a discussion as to why loads are only placed at the joints and the need for a deck system to transfer vehicle loads to the joints on most truss structures used for bridges.

The truss structure used in this example is also a simple truss: a truss that can be created by adding two new members to two existing joints and creating a new joint. Show how this applies when starting with any of the triangles and working from there:



This 2D wooden can be actually loaded. Place the truss on blocks of wood, use a bracket at one end that will allow the bolt connecting the two legs at A to connect as well, use two brackets at the other end that allows the truss to remain vertical but slide at D, and then connect a load to one of the bolts at B or C.

WOODEN TRUSS 3D

STATICS

Keywords: Stability, Strength, Truss

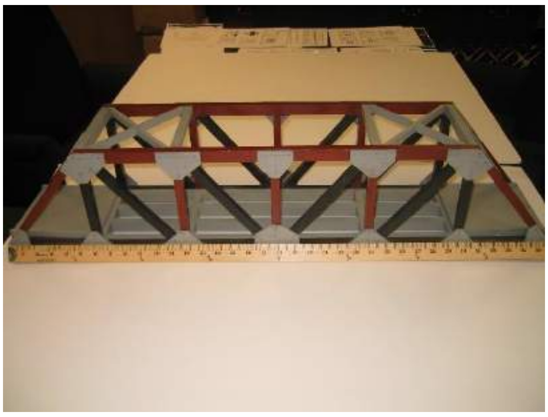
Submitted by: Ronald Welch

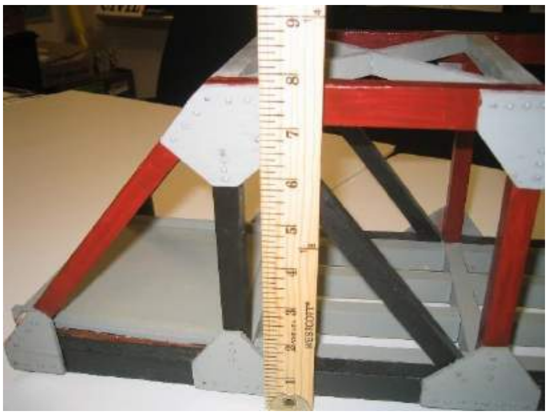
Model Description: This 3D model of a bridge is a model that is very close to a real representation of a bridge. It has a number of realistic features that cannot be shown with K'NEX or other simple structures. This demonstration should take 15-20 minutes.

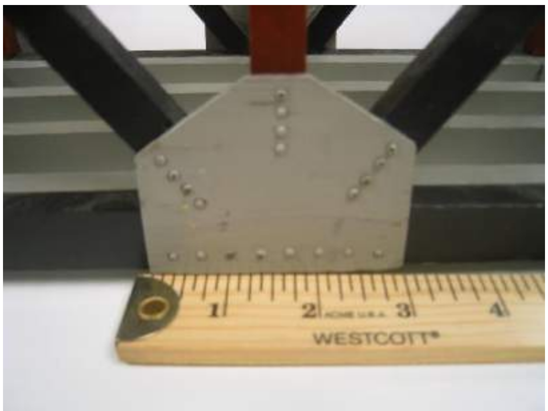
Engineering Principle: Bridges are more than just trusses put together. There are other important factors to a bridge that keep it stable and functional. This bridge uses gusset plates to form joints, a roadway, lateral supports to keep the trusses vertical, supports on both ends, and even curbs. It is also strong enough to hold real loads on its roadway.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Wood	Lots!	$45-60; 2-3 hours	Measurements for the bridge have been included in pictures. It is about a yard long at the bottom, two feet long at the top, and seven inches wide. The members are all about ¾" thick and ½" wide. The plates are each ⅛" thick. The two sections of roadway are 6" x 6" x ⅛" with ⅛" curbs on either side.
Paint	Any	$15	We used three colors: red, black and grey. It adds a nice touch to the presentation.
Nails	Lots!	$10	Nails are used to hold the bridge together.
Car/truck	1	$25	A battery-operated car or truck can drive across this bridge safely.



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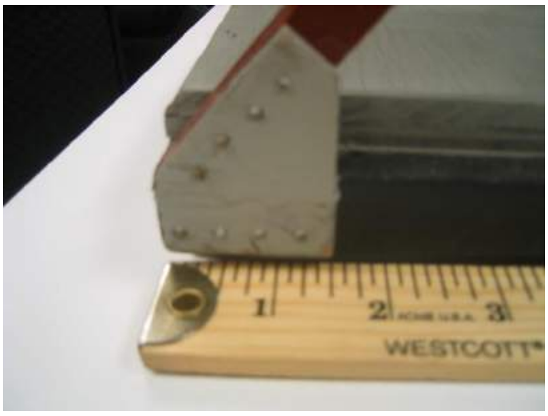
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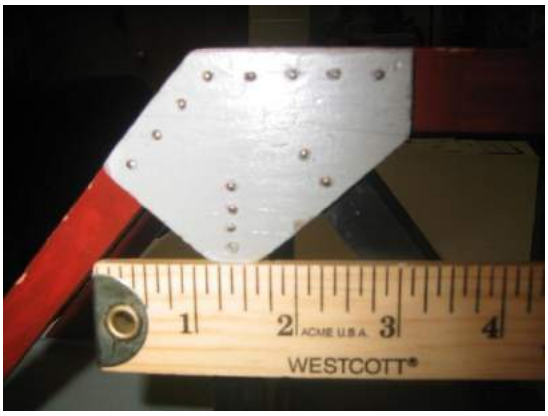
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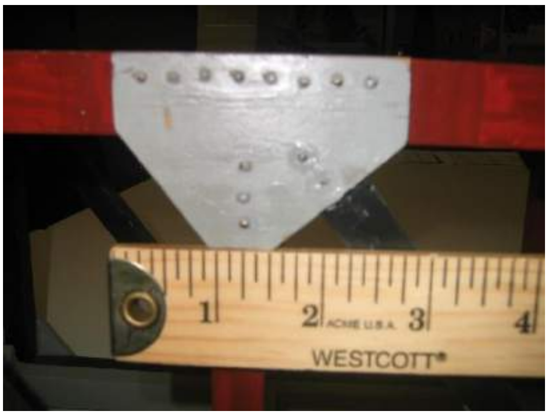
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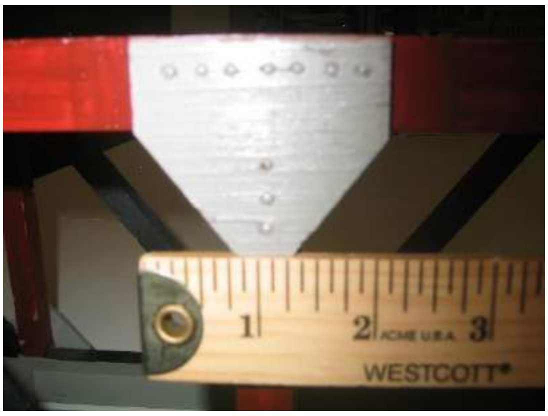
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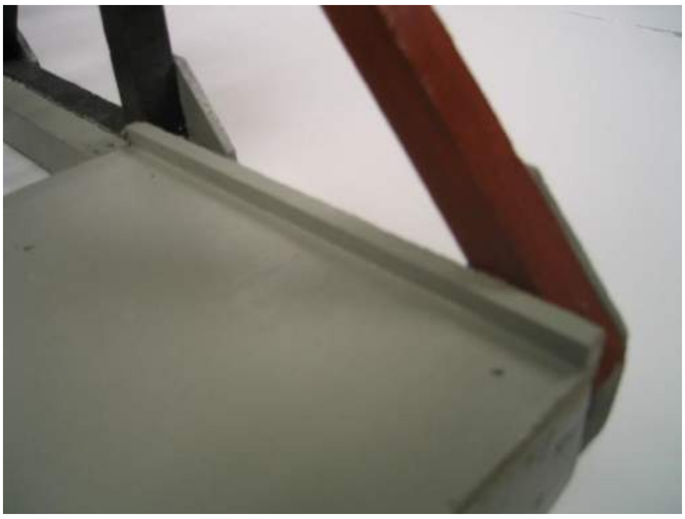
APPLICATION

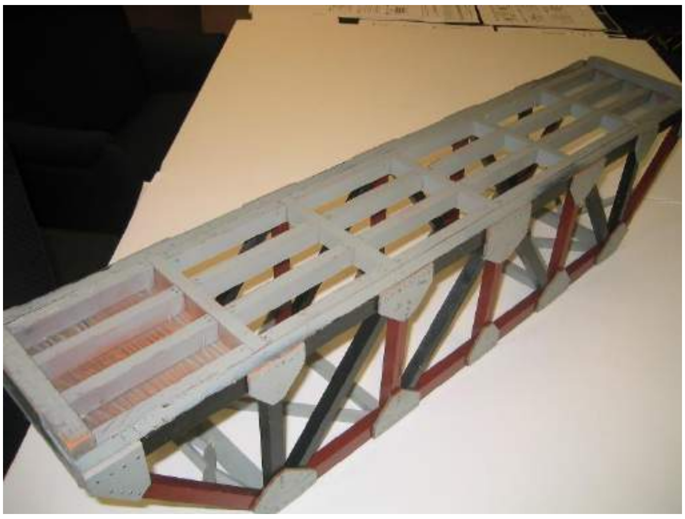
<u>Before Class</u>: Construct the bridge out of the wood and test it with an acceptable load to make sure it doesn't overload and break during class. There is no real requirement to support a load, but it allows additional realism.

<u>In Class</u>: Bring out the bridge and ask the class what distinguishing features represent a real bridge. Talk about each characteristic with the class.

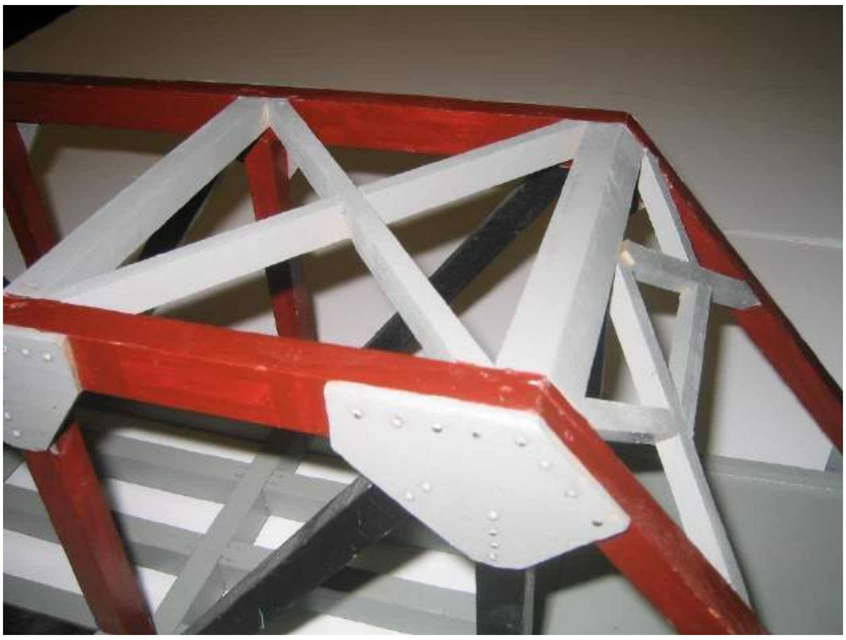
Gusset Plates: This bridge doesn't just have pins to form the joints, it has plates connecting the members that act like pins. The connections for this bridge represent gusset plates connected to members by bolts or rivets. A discussion as to why it still can represent a pin connection should ensue. The forces in the members coming into a joint are intersecting at a single point – a concurrent force system. Therefore, there is no tendency to cause rotation – so can be represented as a pin connection. Demonstrate by putting a load on the roadway. The load is transferred from the roadway to the beams running parallel to the bridge span that transfer the load to a girder running perpendicular to the span that transfers the load to the truss joints where the members are connected by a gusset plate. Therefore, all the members are truss members and the load is only applied at the joints of the truss.

Roadway: Point out the roadway. The load is transferred from the roadway to the beams running parallel to the bridge span that transfer the load to a girder running perpendicular to the span that transfers the load to the truss joints where the members are connected by a gusset plate. Place a load on the road to demonstrate its strength and transfer of load. Could add fun and drama by placing a motorized vehicle on the roadway. Begin explaining how the load is transferred and part of the way through the explanation, make the car or truck drive across the bridge. Also, point out the curbs that are on either side of the roadway and how they add additional load.

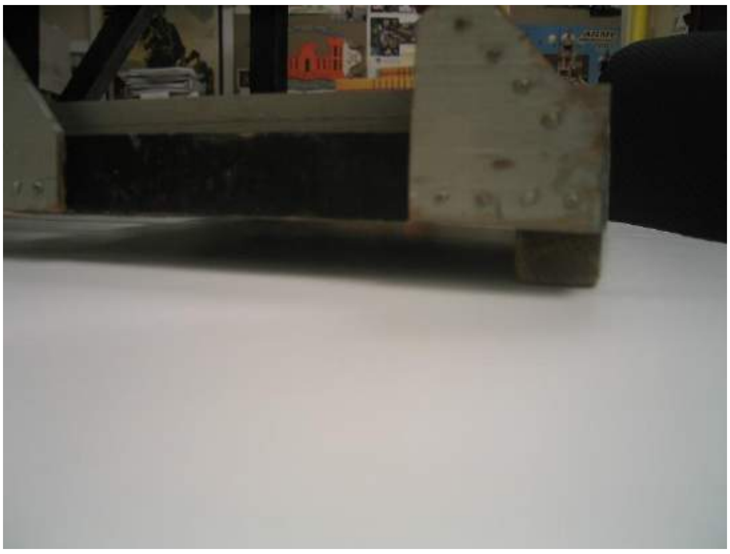




In Class: Lateral supports across the top of the bridge: In real bridges, trusses cannot stay vertical when the loads are applied to them – lateral torsional buckling. Same thing that happens to most long members with a load applied perpendicular to length. This bridge has supports (some forming triangular shapes as well) added to the top to keep the two trusses vertical and prevent lateral torsional buckling.



Partial abutments on either end: The bridge is built with a partial abutment on each end for placement on the two edges of the space being crossed. Abutments are necessary for real bridges and transfer the load from the bridge into the soil.



Additional Application: Using a sturdy wooden structure as described above, real issues such as overhead clearance, lateral supports, abutments, etc. can be discussed. Real looking connections that do not represent idealized pin connections are brought to life.

UNIFORMLY LOADED CABLES

STATICS

Keywords: Cable, Equilibrium, Point Load, Suspension Bridge

Submitted by: Tom Messervey

<u>Model Description</u>: This is an opportunity to hang something from the ceiling and excite the students about their ability to analyze real world structures. After a few weeks of statics lessons, students possess the ability to determine the maximum and minimum force in a cable suspension bridge through equations of equilibrium. This demonstration should take 30 minutes.

<u>Engineering Principle</u>: This physical model provides a visual aid to illustrate the main components of a uniformly loaded cable, or more specifically, a cable suspension bridge. This can be supplemented with a simple board problem that demonstrates distributed loads and how "droop" in the cable from tower to center span can be modeled with simple statics. This statics exercise can be used to demonstrate that the compression in the tower remains constant but the tension in the cable goes down as the towers get taller, which provides a great opportunity to talk about the relationship between statics, design, and cost.

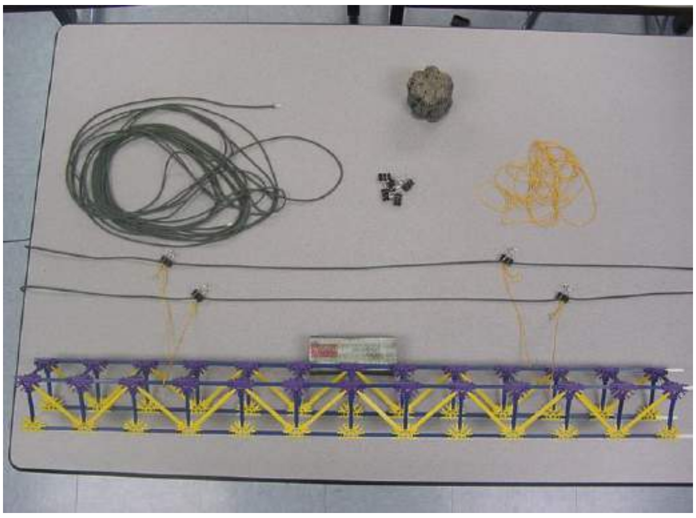
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Rope or Cord	60-80 ft	$20	This is the main cable and varies depending on the size you want to construct
KNEX Truss Deck	1	$150; 45 minutes	Size dependent – construction tips below
String	1 roll	$10	Connects the cables and deck (hangers)
Binder or Alligator Clips	2/string	$5	Clip strings to cables – quick and easy

APPLICATION

<u>Before Class</u>: This can be built once and stored for the following semester. As pictured, seven 3ft sections are utilized but this can vary depending on the size of the classroom and how many KNEX and how much patience the instructor has. Short white connecter pieces allow the sections to quickly connect to each other. Each 3 foot section as pictured below consists of the following KNEX pieces:

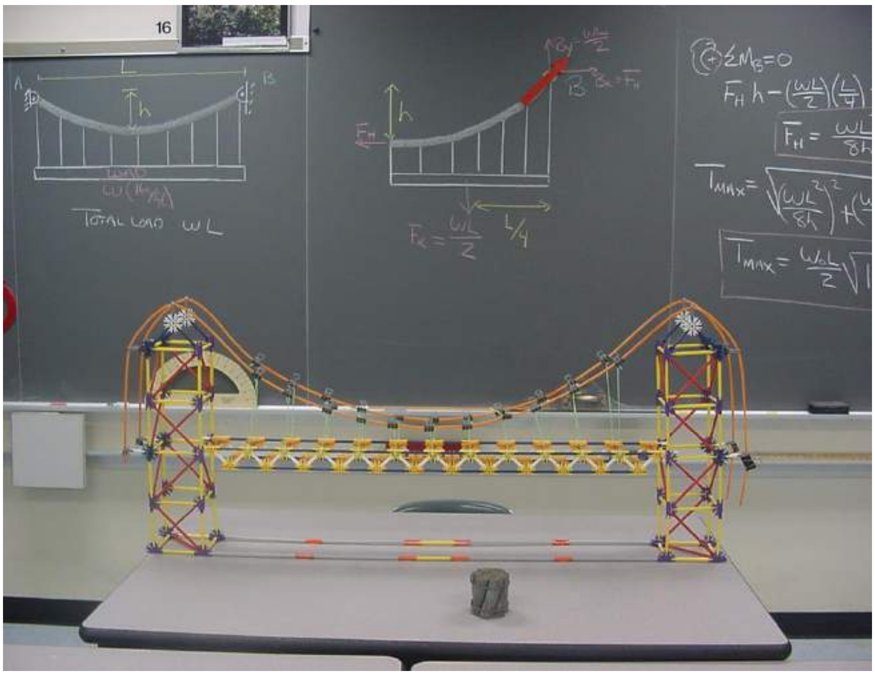
87 ea Blue	52 ea Purple Connectors (compression)
24 ea Yellow	26 ea Yellow Connectors (tension)
4 ea White	



Run the cord (that's the main cable) though some eyelets or hooks in the ceiling and tie off the ends. Stack a couple desks (temporary shoring) on each other to get the deck near its final position. Run the string (that's the hangers connecting the main cable and the deck) through the deck and clip to the main cables (cords). Some raising and adjustment will be necessary – but the student reaction makes it well worth it.

In Class: Discuss the main components of the bridge; main cable, "hanger" cables, stiffening truss and running surface. Use this physical model to really drive home to your students that they have already learned to do something significant in terms of design. During class, it helps to solve for the tension in the main cable and the reactions at the towers. Talk about how varying the tower height effects the forces involved, thereby impacting the cost and aesthetics of the bridge. Also, discuss how a roller at the top of the tower ensures only compressive forces on the tower.

Additional Application: We use this lesson to derive the formula for the maximum tension in the cable through use of a good free body diagram and equations of equilibrium. After this, we watch the Discovery Channel special "Engineering the Impossible: Bridge over the Gibraltar Straight." This 30 minute segment is outstanding. A smaller suspension bridge, an actual wire cable bundle, and FBD are pictured below.



Don't have a ceiling to hang the cable from? No problem – use the students! We have also utilized the same physical model to talk through the different stages of engineering design and construction. Cool!

ZERO FORCE MEMBERS

STATICS

Keywords: Force, Pin, Truss, Zero Force Member

Submitted by: Ronald Welch

Model Description: This is a simple model that will demonstrate the use of zero force members (ZFM) in trusses. Wooden beams are attached with dowels to form a simple truss, which is acted on by an external force. The zero force members are identified by placing a load on a truss and then removing pins at the joints to see if the truss is affected. This demonstration should take 15-20 minutes.

Engineering Principle: The basic equations for equilibrium of a truss joint (Method of Joints) are:

$$\sum F_x = 0 \quad and \quad \sum F_y = 0$$

where the sum of the forces in the x and y direction both equal zero.

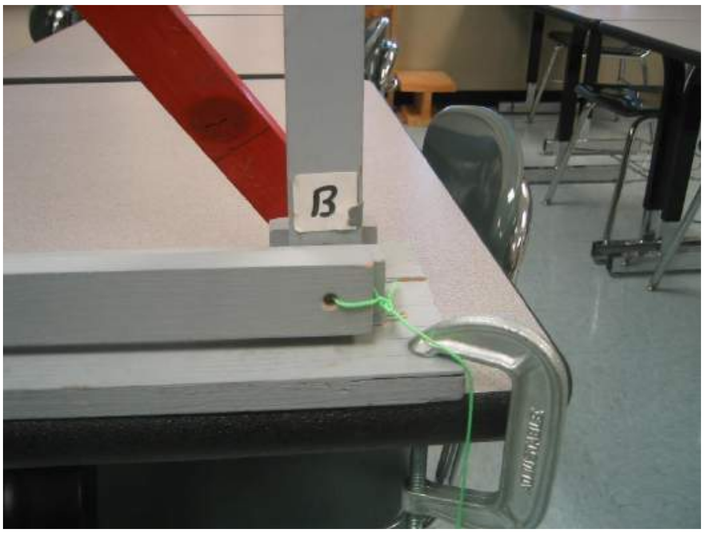
REQUIRED ITEMS

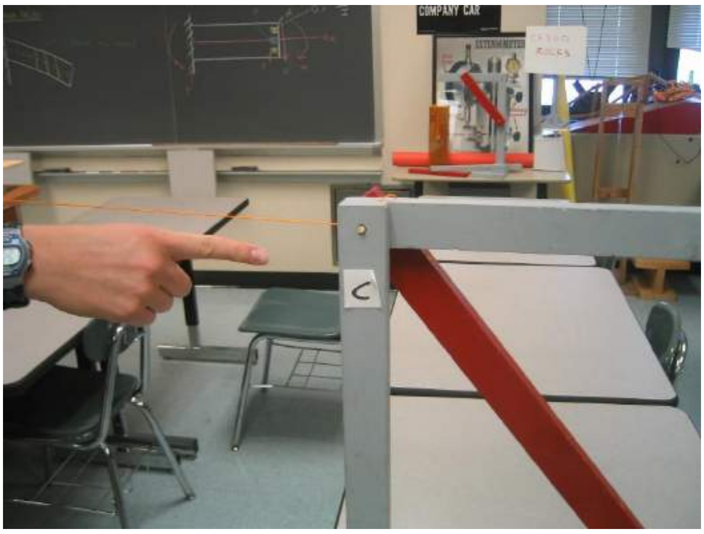
Item	Qty	Cost and Build Time	Description/Details
Wooden members	5	$40; 45 minutes	The vertical members (gray) are 21 in. long. The horizontal members (gray) are 16.5 in. long. The diagonal member (red) is 25.5 in. long. Each member is about 0.75 inch thick and 1.5 inches wide. Each member has a slightly larger than 0.25 inch hole drilled in each end to connect them with 0.25 inch dowels (dowel should slide easily). One of the vertical members has a hook at the level of the connection hole and one of the horizontal members has a hook at one end.
Base	1	$10; 15 minutes	The base is 20 inches long x 6 inches wide x and 5/8 to 3/4 inch thick. The base is used to clamp the ZFM demonstrator to a heavy desk. 4x 1.5 inch tall x 2.25 inch long x 0.75 inch thick pieces nailed to the base provide the supports for the vertical and diagonal members.
Dowels	4	$5	The 4 inch x 1/4 inch dowels will act as pins to hold the members in place.

Item	Qty	Cost and Build Time	Description/Details
Clamps	2	$15 each	Clamps are necessary to hold the truss to the heavy desk/table.
Load (student)	1	Anything but free	The horizontal load applied to the truss will be applied by a student pulling on a string attached to a hook.
Hooks	2	$15	The eye hooks are positioned on either side of the truss on vertical and horizontal members where horizontal load will be applied.
Pliers	1	$15	Any set of pliers will do.
String	1	$5	A moderately strong string is necessary to apply a load to the side of the truss.

APPLICATION

<u>Before Class</u>: Prepare the wooden truss for class and check with test loads to see that it can support a student without risk. Make sure the dowels are in place properly and won't break.





<u>In Class</u>: Ask for a student volunteer to be the load through the string attached to the hook (on the vertical member) on the joint of the truss where three members intersect (Joint C). Have her lean back and close her eyes (drama!). Ask the class what they think would happen if you pulled out any dowel. The dowel at Joint D? You can possibly lead the students to see that the load will flow through the horizontal member to joint D and then down the vertical member (not true, but sets up the drama and the learning point). Hopefully the students will conclude that the student inducing the load will fall down when the pin is pulled. At this point, you may have to work on getting the student to keep her eyes closed. Tell her to trust you since you work for the government (university). Tell her you are about to pull out one of the dowels and to let you know if she feels you pulling it out with pliers. You should be able to pull out the dowel at joint D easily since there is no load in members BD and CD. After a few seconds of continuous talking and with the dowel out and the members dangling (lower by hand so the student cannot feel the movement), tell her to open her eyes with you holding the dowel for everyone to see. Ask her to take her seat and address the whole class about why removing one of the dowels had no effect on the way the truss worked. Work through with the Method of Joints at Joint D and mathematically demonstrate that both members are ZFMs.

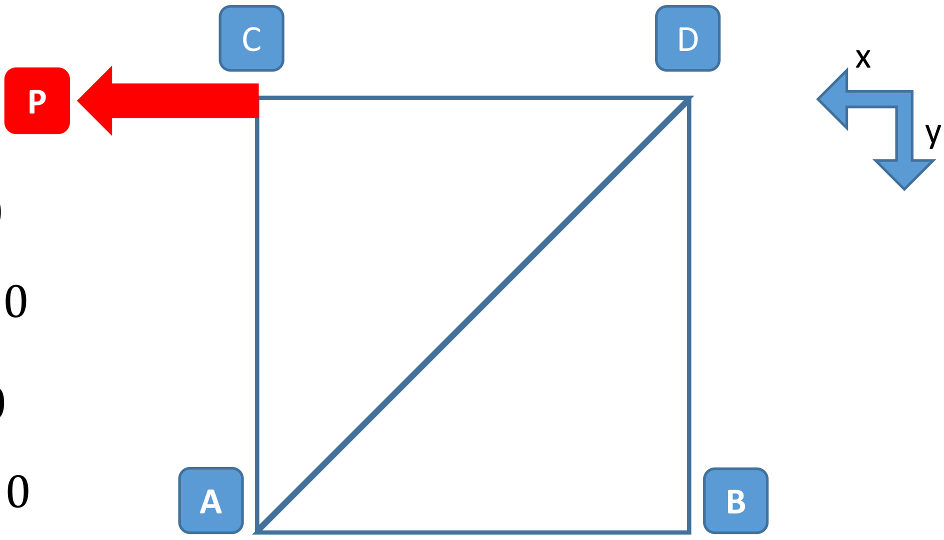

<u>In Class</u>: This example (focusing on joint D) demonstrates a general rule about zero-force members: if there are two members connected at a joint, and the members are non-collinear, and no external load is applied at this joint, then both of these members must be zero force members.

$$\sum F_x = 0$$

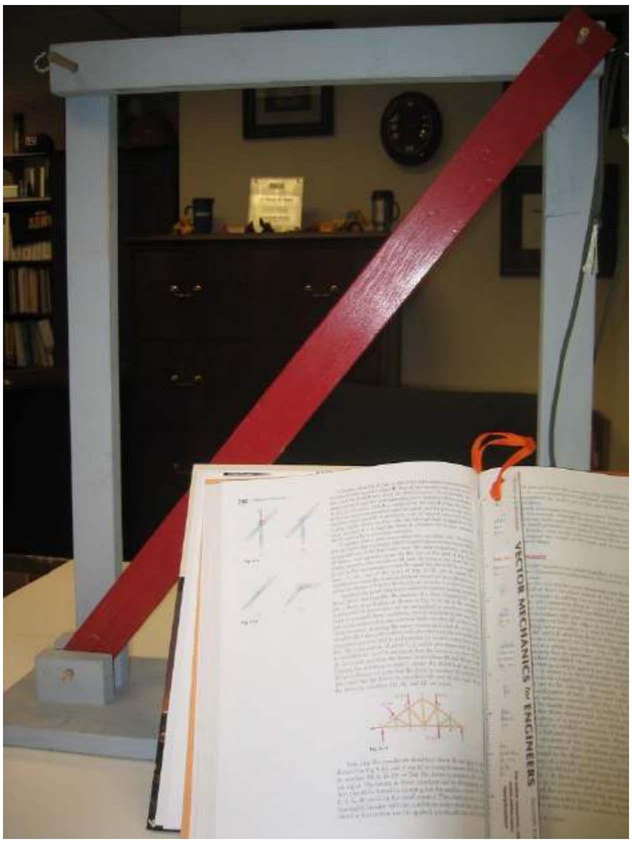
$$F_{CD} = 0$$

$$\sum F_y = 0$$

$$F_{BD} = 0$$

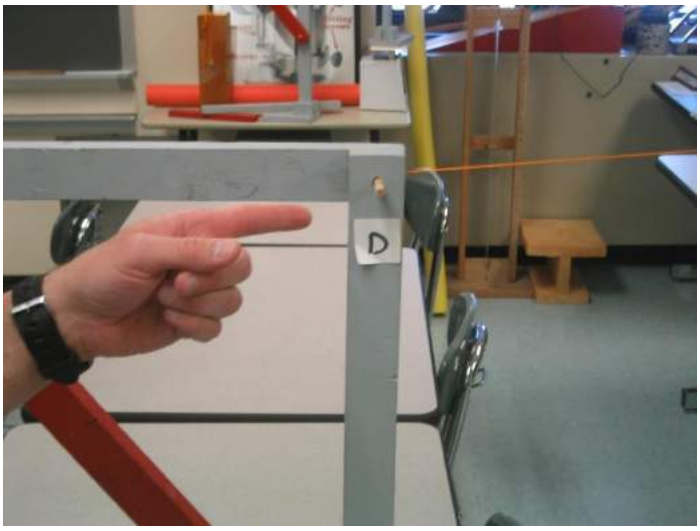


Another general rule about zero-force members is as follows; if three members connect at a joint, two are collinear and the third is non-collinear, and no load is applied at the joint, then the non-collinear member is a zero-force member.



Additional Application: A question should be raised about why these zero-force members are put into trusses. Call a student to the front of the class to demonstrate what happens when you move the load to Joint D. Move the string from Joint C (hook on the vertical member) to the opposite side of the truss at Joint D (hook on the horizontal member) and have the student pull on the string once more. Ask her to lean back and shut her eyes – which she will probably do more quickly as the trust has been developed. Try to remove the dowel, and show that its removal would require much effort. Tell the student to sit down before she hurts herself (with the hook on the horizontal member, she will not fall down since the horizontal member is still connected at Joint C). Work through with the Method of Joints at Joint D to explain that the member that was zero-force member (horizontal member) under one condition is no longer a zero-force member under this new condition. The reason for ZFMs is that the load may move to another joint and ZFMs may be required to support the load at the new location. Sometimes ZFMs are used to support members in compression with the ZFM connected at the mid-point of the member in compression. Shortening the length of the unsupported section can actually strengthen the compression member by a factor of 4. This can be demonstrated using a wacky fun noodle – see Wacky Fun Noodle demonstration.

If you really want to pull the pin at D with the student creating a horizontal load, the hooks can be screwed into the end of the horizontal member instead. When the pin at D is pulled, the student is still supported by the horizontal member that is still connected to the stable triangular truss structure at Joint C.



THERMODYNAMICS

DIRECTION OF THE 2ND LAW

THERMODYNAMICS

Keywords: Clausius Statement, Entropy, Order

Submitted by: Richard Melnyk

Model Description: This is not a hands on demonstration, but a visual aid designed to generate discussion about the Clausius statement of the 2nd Law. This activity should take 5-8 minutes.

Engineering Principle: The Clausius statement of the 2nd Law states "It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower temperature body to a higher temperature body." Explicitly, this statement specifies the direction of heat transfer that will occur spontaneously. However, the larger implication of this statement and the 2nd law is that all processes must occur in a specific direction leading toward greater disorder.

Which picture was taken first?

APPLICATION

Before Class: Prepare the pictures below in a slide show of some type.

In Class: Display the two pictures of the wine glass pictured above. Explain to the students that both pictures are of the same glass at different times. Ask which picture was taken first in a timeline. This question will generate discussion about order and disorder. Most students will intuitively guess that the intact glass is first in the sequence and the broken glass is next. This is because we have all been subject to the 2nd Law our entire lives without expressly understanding it. The instructor can then use this question to begin discussion of the Clausius statement and the implications of the 2nd Law.

Additional Application: Inevitably, a student will comment that the broken glass could have been the first picture in the sequence and that if someone put it together perfectly, the intact glass could be the subsequent picture. This statement is partially true and will help generate discussion on the 2nd Law internally, externally, and as a total system. Ask the student to define the system boundaries if you choose to fix the broken glass. The system in that case will include the glue, the broken glass and the "mechanic". Explain that the entropy of the glass may have decreased but the entropy of the entire system has increased.

LOSSES AND THE 2ND LAW

THERMODYNAMICS

Keywords: Conservation of Energy, Kelvin-Planck Statement

Submitted by: Richard Melnyk

Model Description: This is a demonstration designed to generate a conceptual discussion about the 2nd Law of Thermodynamics and the Kelvin-Planck statement of the law in particular. It utilizes a pendulum to introduce the concept of irreversibilities due to friction. This demonstration should take 10-15 minutes.

Engineering Principle: This demonstration is based on the assumption that the course has already spent time covering the 1st Law of Thermodynamics (Conservation of Energy) and is about to transition to the 2nd Law. By now, students should be familiar with the principles of conservation of energy from Thermodynamics and 2-D motion from Physics: $E = KE + PE + U$.

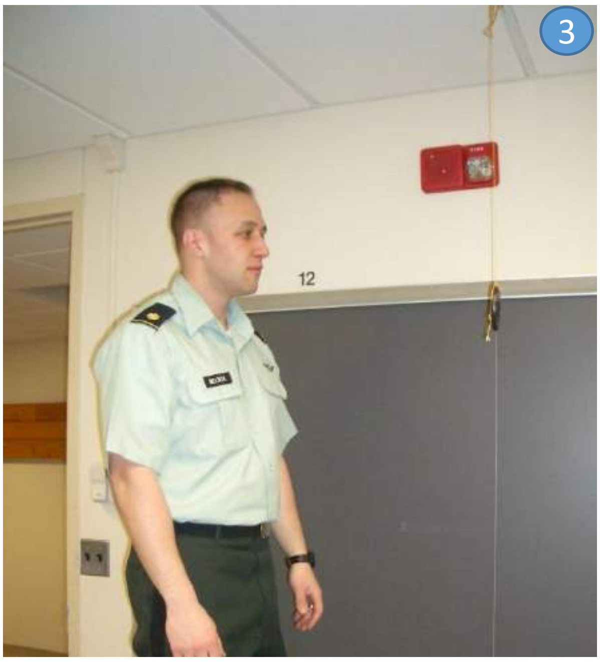
REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
String	1	\$3-5	A length of 2-3 ft will do in most classroom environments
Weight	1	\$5-10	Any object can be used as a weight provided it will not damage the classroom ceiling.
Chair	1		The demonstrator will need something to stand on during the demo.

APPLICATION

Before Class: Obtain the materials above and suspend the weight from the ceiling in a location where it will not impede the rest of the class, but is visible to students. Ensure there is sufficient room for the weighted object to swing without striking a wall or other object. 1

<u>In Class</u>: After a discussion on energy and how energy is conserved, discuss the pendulum. Based on simply analyzing the kinetic and potential energy of the pendulum, the object should return to its original height if displaced and then allowed to oscillate. Ask if the students believe that premise and then offer to demonstrate the principle by standing on the chair and placing the weight on the tip of your nose or chin. 2 Allow the weight to drop 3 (do NOT push it during the release, or you may get smacked in the nose!), and then ensure you do not flinch as the weight rises, falls and then rises again just missing your face. At this point, a discussion can begin about losses, friction and irreversibilities. This will act as a bridge into discussion of the 2nd Law and the Kelvin-Planck statement of the law.



Observations: Students should be able to eventually understand how the 1st Law can still be satisfied while conforming to the 2nd law. The irreversibilities that prevent full recovery of the original potential energy manifest themselves as internal energy or the heat produced by friction between the string and ceiling and ambient air. While this is too negligible to accurately measure in the classroom it can be demonstrated by having the students rub their hands along the desks.

<u>Additional Application</u>: The demonstration has the potential to inject some drama into the classroom. Ask the students if they think the weight will return and smack you in the face. If people disagree you can step off the chair and discuss the problem once or twice before actually accomplishing the demonstration to add suspense.

THE HAND BOILER

THERMODYNAMICS

Keywords: Boiling Point, Ideal Gas Law, Pressure, Temperature, Volume

Submitted by: Phil Root

Model Description: This is a demonstration of how pressure increases with temperature particularly at temperatures above the fluid's boiling point. Warming the bottom chamber beyond the boiling point increases the pressure sufficiently to displace fluid into the upper chamber. This demonstration should take 5 minutes.

Engineering Principle: The pressure of a fluid increases as you increase temperature. This relation is more dramatic when heating a vapor. For an ideal gas, the equation of state is governed by Equation 1 where ***P*** is the absolute pressure, ***v*** is the specific volume, ***R*** is the gas constant and ***T*** is the absolute temperature.

$$P\,v = R\,T \qquad (1)$$

Warming the fluid within the hand boiler above its boiling point causes the pressure within the lower chamber to increase drastically, and this pressure is sufficient to displace the remainder of the fluid to the upper chamber.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Hand Boiler	1	$5	Available from such sources as Steve Spangler Science (www.stevespanglerscience.com) and Copernicus Toys (www.copernicustoys.com).

APPLICATION

In Class: Grasp the hand boiler. 2 The temperature in the lower chamber will rise to above the boiling point for the fluid very quickly, and this will cause the displacement of the fluid from the lower to the upper chamber. As you continue to grasp the hand boiler, vapor bubbles will rise through the glass straw giving the appearance that the upper chamber is boiling. *Observations*: Students should be able to visualize the effect of raising the fluids temperature above the boiling point and the ensuing increase in pressure in the lower chamber.

Additional Application: Ask students how to get the fluid to return to the lower chamber without turning it over (you can hold the upper chamber).
See which students have the warmest hands by passing the boiler around and clocking the time required to move all the fluid to the upper chamber.

BOILING PROPERTIES

THERMODYNAMICS

Keywords: Boiling, Pressure, Temperature

Submitted by: Michael Rounds

Model Description: This demonstration is designed to show that the boiling point temperature of water is dependent on the pressure. This demonstration should take 8-10 minutes.

Engineering Principle: Most students are familiar with the process of boiling water on a stove, but this demonstration will show that the phase change is dependent on both pressure and temperature. This demonstration is best used in a Thermodynamics course when the topic of thermodynamic properties of water, saturation temperature and saturation pressure, the vapor dome, and the property tables for water are introduced. It is designed to provide students with a basic understanding of saturation pressure and saturation temperature and illustrate the dependence of the properties Pressure and Temperature when a substance is undergoing a phase change.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Vacuum Chamber	1	$110	Container with a clear plastic lid, exit port, and rubber seal between the base and the lid.
Vacuum Pump	1	$300	Electric-powered vacuum pump.
Plastic Tubing	1	$15	Connects vacuum pump to the pressure chamber.
Glass beaker with water	1	$10	Water should be lukewarm or warm depending on the strength of the vacuum pump.

APPLICATION

Before Class: Have the components set up in the classroom. 1

In Class: Discuss the boiling point of water. Students are familiar with boiling water on a stove and will usually answer that the boiling temperature of water is 100° Celsius. Point out that the correct answer must include “at one atmosphere pressure”. Point out that water boils at a lower temperature at high altitudes where the atmospheric pressure is lower and at higher temperatures when pressures are above atmospheric pressure. Introduce the demonstration by asking how we can get the water in the beaker to undergo a phase change. We can either use a hot plate to raise the temperature of the water to 100°C, or we can reduce the pressure around the beaker of water low enough that the water will boil at it’s current temperature. 2

Observations: Students should be able to see vapor bubbles forming in the water in the beaker and then the water come to a rolling boil as the vacuum pump is turned on and evacuates the air from the pressure chamber. 3

Additional Application: To increase the suspense, put a cover over the vacuum pump and tell the students that you are going to boil water with a mystery device. Once the water has come to a rolling boil, release the pressure, lift off the cover and pick up the beaker with an oven mitt. Take it around the class and have a brave volunteer check the water temperature by sticking their finger into the beaker. After this demonstration, discuss saturation temperature and saturation pressure and the dependence of those properties during a phase change of a substance. Next, introduce the water property tables in the back of the Thermodynamic textbook and provide several examples such as using a pressure cooker at high altitudes, vacuum cooling of vegetables, and refrigerants used in air conditioning and refrigeration. Finally, use various combinations of temperature and pressure for water undergoing a phase change to vapor to construct Pressure vs Specific Volume and Temperature vs Specific Volume plots that show the vapor dome.

CLOSED VS OPEN SYSTEMS

THERMODYNAMICS

Keywords: Conservation of Energy, Conservation of Mass

Submitted by: Seth Norberg

Model Description: This is a demonstration of the basic principles open and closed systems. It reinforces the conservation of mass and energy. This demonstration should take 5-8 minutes.

Engineering Principle: Most students have a basic understanding of open and closed systems, but tend to get lost in the terminology. In order to assist in the student's internalization of the concept of open vs. closed systems, this demonstration shows the differences between them in an easily understandable method.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Soda Can	1	$0.50	It must not be opened.
Pitcher of Water	1	$5	Half full

APPLICATION

<u>In Class</u>: Highlight the conservation of mass:

$$0 = \frac{dm_{cv}}{dt} + \sum_e \dot{m}_e - \sum_i \dot{m}_i$$

For a closed system, there is no mass passing the boundary, so mass is conserved within the system. Using your un-opened soda can, rotate the can and ask the class what they expect to happen. Obviously, the contents will not spill out—the mass can not cross the boundary of the system.

Then open the can, and drink some soda. The mass is crossing the boundary of the system at the opening. At this point, question if the flow of mass across the boundary is steady, and how the $\frac{dm_{cv}}{dt}$ term will be affected by the draining of the can.

From the conservation of mass, the conservation of energy can be interpreted. What will happen if we leave the un-opened cold soda in the warm classroom? The soda will get warmer, thereby showing that heat can transfer across the boundaries of a closed system.

If we open the cold soda, we notice that the can itself is cold on our hand and that the mass of soda going down our throat is cold. This shows that energy in an open system can be transferred with mass entering or exiting and / or through the boundary of the system.

Observations: Students should be able to observe how mass can not cross the boundary of the closed system (un-opened can) and how it is draining out of the open system (opened can). Students should also be able to recognize the heat transfer across the can itself (open or closed system) as well as with the mass as it drains out of the can (open system).

<u>Additional Application</u>: When introducing the 2nd Law of Thermodynamics, re-introduce the cold can of soda. In order to show how the 2nd Law predicts direction, ask which direction the heat must transfer. Will the opposite violate the 1st Law? Additionally, pour the contents of the soda into a pitcher of water. Will the soda and water unmix spontaneously?

MOLASSES MADNESS

THERMODYNAMICS

Keywords: Conservation of Mass, Incompressible Fluid, Velocity

Submitted by: Phil Root

Model Description: This is a demonstration of the concept of conservation of mass. By pouring an incompressible fluid (molasses), it is clearly demonstrated that as the velocity of the flow increases, the cross-sectional area of the flow must decrease. 1 This demonstration should take 8-10 minutes.

Engineering Principle: Mass is conserved when the mass flow rate into the system equals the mass flow rate out of the system:

$$\dot{m}_{in} = \dot{m}_{out}$$

The mass flow of a fluid at any point is the product of the density, cross-sectional area and flow velocity. Therefore, we can rewrite the conservation of mass between points one and two as:

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

The density of molasses is assumed constant between points one and two and equation (2) reduces to:

$$A_1 V_1 = A_2 V_2$$

If the cross-sectional area of the flow decreases ($A_2 < A_1$), then the flow velocity must increase to maintain the conservation of mass ($V_2 > V_1$).

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Jar of Molasses	1	\$3-5	Any kind will do.
Beaker	1	\$10	Any kind of cup will suffice to collect the molasses
Wet Paper Towels	5-10	\$2	Used for the inevitable mess

APPLICATION

<u>Before Class</u>: Open the jar of molasses as it will inevitably be stuck shut otherwise during class.

<u>In Class</u>: After a discussion of the conservation of mass, pour the molasses from the jar or a cup into the beaker. The cross-sectional area of the flow initially (A_1) is large and the flow velocity (V_1) is low. As the flow accelerates due to gravity, the downstream velocity (V_2) increases. 2 As this velocity increases we see the cross-sectional area (A_2) decrease. 3

Observations: Students should be able to observe how the cross-sectional area decreases as the velocity increases.

<u>Additional Application</u>: Ask the students for common examples where we increase the flow velocity by decreasing the area (i.e. shower head, squirt gun, etc.) Using these examples, draw a schematic of the device illustrating the conditions at points one and two.

THE LAVA LAMP – DENSITY AND BUOYANCY

THERMODYNAMICS

Keywords: Archimedes Principle, Buoyancy, Density

Submitted by: Phil Root

Model Description: This is a demonstration of the relationship between density and buoyancy. It reinforces the concept that fluids that are less dense have a higher buoyancy. In the case of the lava lamp, this causes the "lava" to rise vertically as heating causes its density to change. This demonstration should take 3-5 minutes.

Engineering Principle: Archimedes Principle states that the buoyant force acting upward on a body is equal to the weight of the fluid displaced by the floating body.

$$F_B = \rho_{fluid}\, g\, V_{body}$$

In this demonstration, a lava lamp demonstrates the buoyant force acting on a mass of translucent wax. The wax is initially on the bottom of the lamp where the light bulb at the bottom heats it. As the mass of wax heats, its density decreases and its volume increases. Archimedes principle states that as the volume of molten wax increases, the buoyant force acting upon it also increases. At some critical temperature and volume, the density of the wax is less than the density of the surrounding fluid, and the mass of wax rises. Once at the top of the glass, the wax cools slightly, and its volume decreases as its density increases. The wax mass then descends to the bottom of the lamp where the cycle repeats.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Lava Lamp	1	$15	Translucent wax is preferable

APPLICATION

<u>Before Class</u>: Plug in the lava lamp at least 45 minutes prior to class.

<u>In Class</u>: After a discussion of buoyancy and density, unveil the lava lamp. Note that the density of masses of wax that are rising must be less than the surrounding fluid. Similarly, masses that have cooled at the top of the glass are now denser than the surrounding fluid.

Observations: Students should be able to see the effect of varying density and volume upon the buoyant force.

<u>Additional Application</u>: For a tangential discussion, note that lava lamp have been used to initialize to create random numbers due to the chaotic nature of convective heating.

Ask a student if the lava lamp behavior would change in a very hot or cold room. If the room is too cold, the wax would never warm to the point where the wax masses rise. Conversely, if the room is too warm, the wax would rise to the surface and never descend.

ENGINE KNOCK

THERMODYNAMICS

Keywords: Compression, Otto Cycle

Submitted by: Justin Highley

Model Description: This is a training aid that can be used during the discussion of engine knock in internal combustion engines, and to show the severe damage it can cause to engine components. This demonstration should take 5-8 minutes.

Engineering Principle: Engine knock, or autoignition is the premature ignition of the fuel-air mixture in a reciprocating engine, and occurs when the temperature in the cylinder exceeds the autoignition temperature of the fuel-air mixture. This spontaneous ignition results in very high pressures within the cylinder and the “pinging” sound most people associate with engine knock. Autoignition is normally caused by high compression ratios, low octane fuel, or a combination of the two. High compression ratios can cause engine knock because the temperature at the end of compression is a function of the compression ratio. Using an ideal engine cycle analysis (Otto Cycle) and cold air standard assumptions, this temperature is found using the equation:

$$T_2 = T_1 r^{k-1}$$

where:
T_1 = Temperature of fuel air mixture before compression
T_2 = Temperature following compression
r = compression ratio
k = ratio of specific heats (1.4 for air)

Based on this relationship, one can see that as the engine’s compression ratio increases, so does the temperature of the fuel air mixture. However, higher compression ratios also lead to higher net power output, which is why high performance engines normally have higher compression ratios (10+). To overcome the tendency for autoignition, these engines use high octane fuels. Octane rating is simply a measure of a fuel’s knock resistance – the higher the rating the more resistant a fuel is to engine knock. When the octane rating is too low for a given compression ratio, engine knock can occur. The resulting high pressures travel through the cylinder, placing severe stress on the engine. Additionally, the ignition occurs during the piston’s upstroke, which severely decreases the engine’s power output.

REQUIRED ITEMS

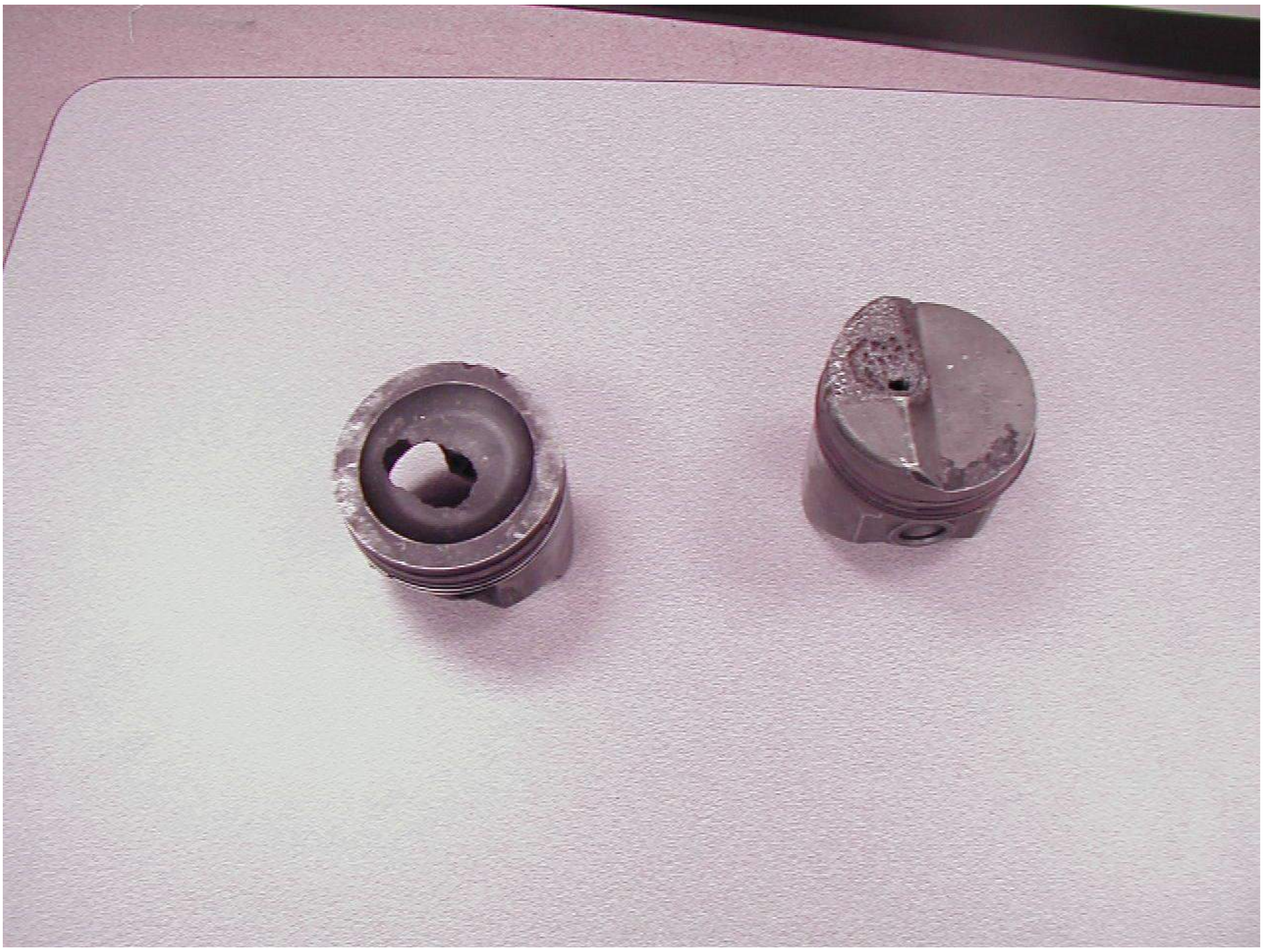
Item	Qty	Cost and Build Time	Description/Details
Damaged Engine Pistons	Various	$15-25	Engine Knock can result in critical failure in several ways. Most pistons damaged due to knock will have holes in them.

APPLICATION

Before Class: Obtain damaged piston(s) and place them out of sight to be pulled out at the appropriate time during class.

In Class: When discussing the concept of engine knock, address the effects of compression ratio and octane rating on engine performance. Pass the damaged piston(s) around the class.

Observations: Students can see the adverse effects of engine knock and the extreme results.



Additional Application: This class can also lead into a discussion of leaded fuels (high knock resistance but toxic by-products) and the advent of advanced refining methods to obtain higher octane fuels. This is a good way to tie in the social, political, and economic impact engineers have on society.

PSYCHROMETRY

THERMODYNAMICS

Keywords: Adiabatic, ASHRAE, Wet Bulb

Submitted by: Richard Melnyk

Model Description: This is a demonstration designed to introduce the basic concepts of psychrometry, the adiabatic saturation or wet bulb temperature, sling psychrometers and the ASHRAE comfort zone. This demonstration should take 8-10 minutes.

Engineering Principle: This demonstration is best used in a Thermodynamics course when the topic of psychrometrics is introduced. It is designed to provide students with a basic understanding of air-water vapor mixtures, how a sling psychrometer works, and how to plot a state point on a psychrometric chart.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Thermometer	2	$10 each	Simple, mercury thermometers work best.
Cloth wick	1	$5	A piece of cloth to cover the bulb of one of the thermometers.
Bracket	1	$5-10; 30 minutes	Some device to hold the two thermometers together and expose the bulbs to ambient air.
Chain or string	1	$2-5	Approximately 6-8 inches to allow the user to sling the psychrometer through the air.

APPLICATION

Before Class: Build or obtain the components to build the sling psychrometer. 1 Also, obtain a copy of the psychrometric chart from ASHRAE. A version of this chart appears in the FE Reference Manual and in many Thermodynamics textbooks. A technique is to enlarge the chart on an easel or in a PowerPoint presentation in addition to giving a copy to each student.

In Class: Discuss the psychrometric chart, how to read it, and explain the concept of the comfort zone. Discuss the psychrometer, and the concept of the adiabatic saturation temperature. Demonstrate the sling psychrometer 2 and record the values of the dry and wet bulb temperatures. Plot these points on the psychrometric chart to determine whether the room is in the comfort zone. This can also lead to a discussion on air-conditioning processes such as heating, cooling, humidification and de-humidification.

Observations: Students should be able to see how the temperature changed on the wet bulb thermometer after the demonstration. Ask the students if the change in temperature would be larger or smaller if the air had a higher humidity ratio.

Additional Application: Develop a scenario early in the lecture in which one person in the class has the task of determining whether the classroom is in the comfort zone or not. Then develop the definitions of dry air, water vapor, mixtures, humidity ratio, and relative humidity. None of these terms will present a particularly easy method of determining if the room is in the comfort zone or not. Finally, introduce the adiabatic saturation temperature term and the sling psychrometer. Time the demonstration so that it occurs near the end of the lecture to build suspense toward the final determination of the state of the room. Pick up next lesson with total air-conditioning processes (if taught) as a transition to how to move into the comfort zone.

TOTAL ENERGY – FAN BOX

THERMODYNAMICS

Keywords: Energy Transfer, Work

Submitted by: Richard Melnyk

Model Description: This is a demonstration of the basic principles energy and energy transfer. It reinforces the concept that internal energy is one of the three forms of energy and that energy can be transferred as work. This demonstration should take 15 minutes.

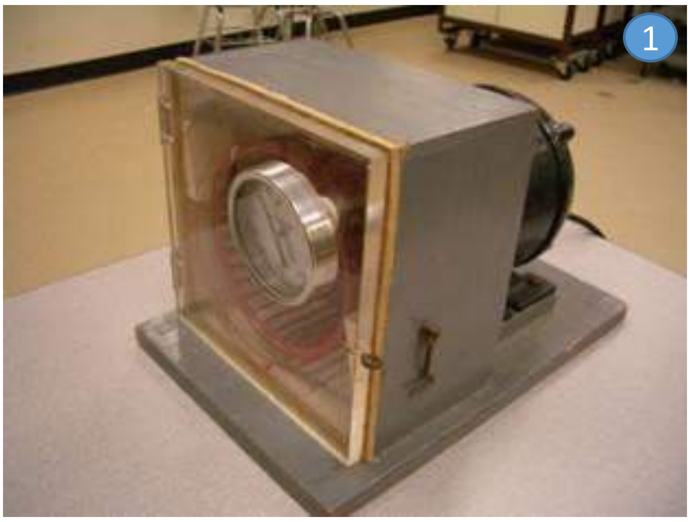
Engineering Principle: Most students arrive to their basic Thermodynamics course with an understanding of kinetic and potential energy. However, they may not be as familiar with internal energy and how energy is transferred via work. This demonstration reinforces the 1st Law of Thermodynamics for a stationary, closed system.

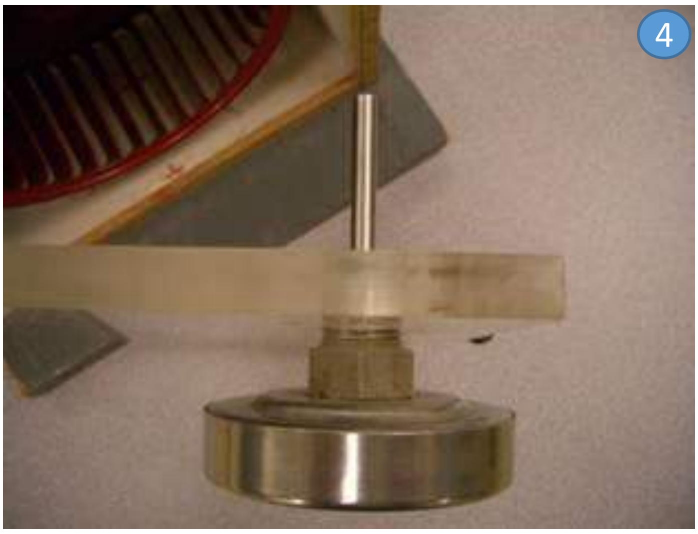
$$Q - W = \Delta U$$

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Electric Motor	1	$100	Small electric motor with a shaft output.
Fan	1	$15	A small fan (centrifugal or 'squirrel cage') attached to the shaft of the electric motor. You need to agitate the air inside the fan box in order to increase the Internal Energy, thereby raising the temperature inside the box.
Plexiglass box	1	$30	Used to encase the fan.
Thermometer	1	$10	Mounted inside the plexiglass case, near the fan.
Cardboard Box	1		Used to hide the fan box prior to the demonstration. Cut a hole in the box to allow students to see the thermometer display.

Total build time estimated to be 2-3 hours.

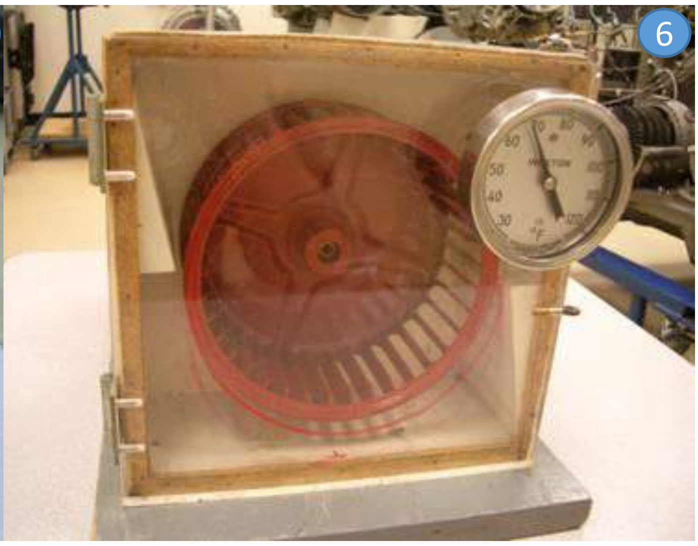




APPLICATION

<u>Before Class</u>: Obtain the proper materials and build the fan box device. The fan box above uses an electric motor with an output shaft. The motor used was 1/6 hp, but that exact power is not necessary. The motor is mounted to a flat, wooden platform to hold the motor and box in place. The box itself consists of a wooden case approximately 12” high by 12” wide. The exact dimensions are left to the user, but it must be deep enough to house the centrifugal fan inside. The front face of the box is plexiglass and hinged to allow the door to open. A standard thermometer is drilled into the plexiglass to allow the temperature probe to sit near the outer edge of the centrifugal fan. Smaller wooden wedges are placed around the corners of the box to reduce the amount of air in the box around the fan. 1 2 3 4

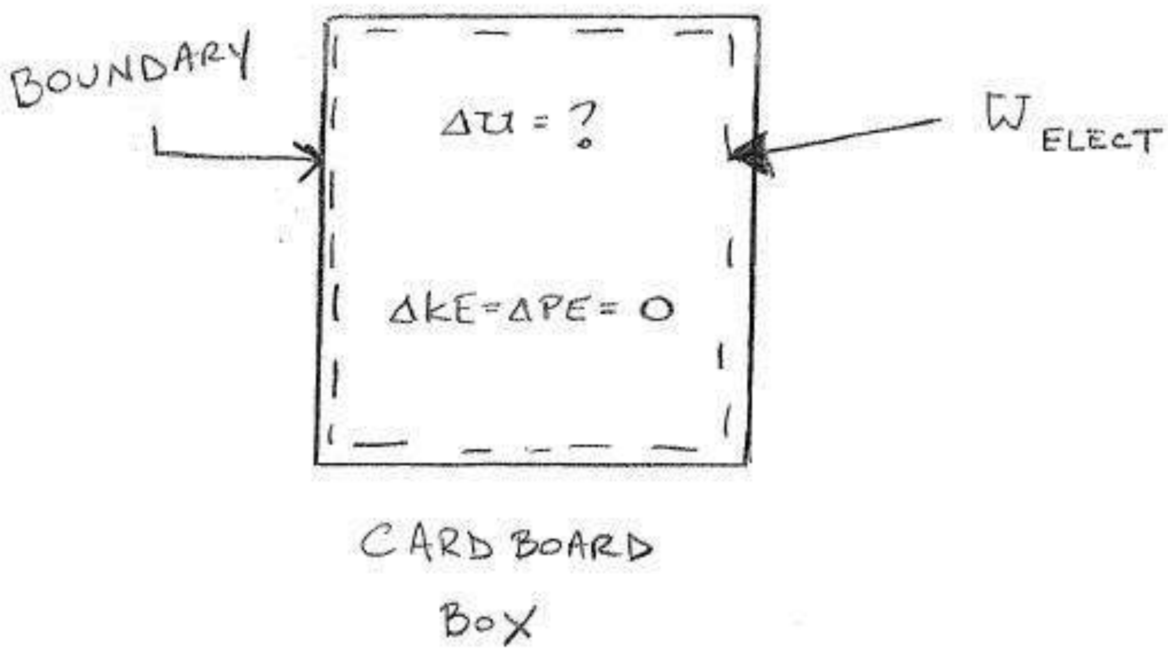
<u>In Class</u>: After a discussion on energy and energy transfer, observe the temperature on the thermometer inside the ‘mystery device’. 5 Then turn on the fan and observe the temperature rise. Ask questions about what could cause the temperature inside the device to rise. Tie the conversation back to the concept of Internal Energy. At this point, many students will assume there is some type of heating element inside the device, neglecting the fact that work is also a form of energy transfer. Finally, remove the cardboard box revealing the fan inside the plexiglass container 6 , and discuss the differences between heat transfer and work.



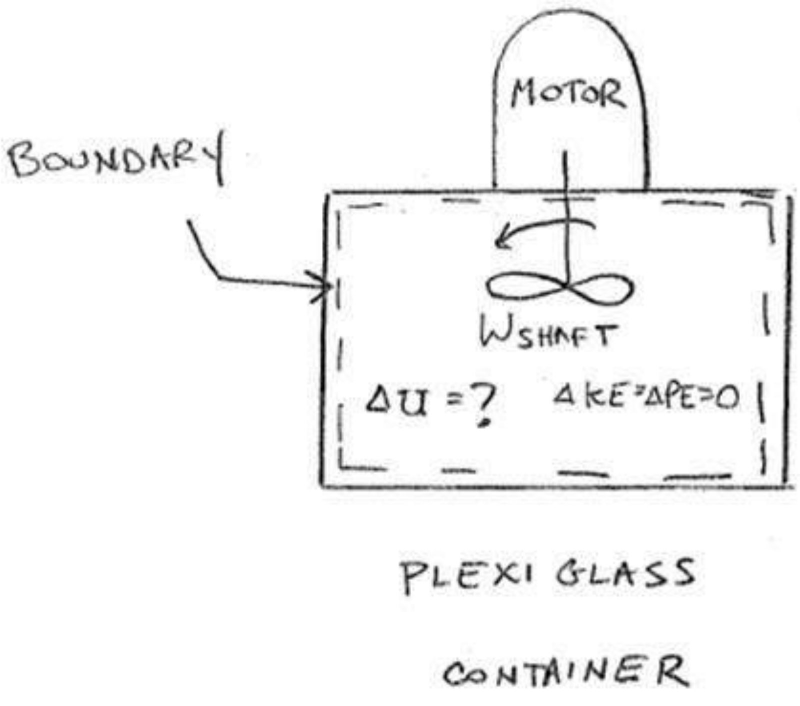
Observations: Students should be able to observe how electrical energy is converted to mechanical energy from the wall outlet to the fan shaft. They can then observe how that mechanical energy is transferred to the air inside the fan box in the form of Internal Energy, as evidenced by the rise in temperature inside the box.

<u>Additional Application</u>: After the demonstration have the students draw a schematic of the device with the cardboard box as the boundary. In this case, the electrical energy is the only energy transfer across the boundary 7. Then, have the students draw the system again with the plexiglass container as the boundary 8. Discuss how the interactions are different, based on how you choose the system boundary.

SCENARIO 1: 7



SCENARIO 2: 8



TOTAL ENERGY

THERMODYNAMICS

Keywords: Internal Energy, Kinetic Energy, Potential Energy, Total Energy

Submitted by: Phil Root

Model Description: This is a demonstration of the concept of total energy. There are three principle components to total energy for introductory thermodynamics: potential energy, kinetic energy, and internal energy. This demonstration should take 3-5 minutes.

Engineering Principle: Total energy is the sum of all forms of energy for a system. In introductory thermodynamics it is convenient to ignore electrical, magnetic, nuclear, and related forms of energy. Thus we can simplify our definition of total energy as the sum of the potential (PE), kinetic (KE), and internal energies (U).

1 $E = PE + KE + U$ 2 $PE = m\,g\,h$ 3 $KE = \frac{1}{2} m V^2$

Equation 2 states that the potential energy of a system is the product of the mass (m), gravitation acceleration (g) and the height (h) above some reference. Similarly, the kinetic energy is proportional to the mass and the square of velocity. An increase in any of these three forms of energy increases the total energy of the system.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Tennis Ball	1	$3	

APPLICATION

In Class: After a discussion of the components of total energy, hold up the tennis ball. Compare the increase in potential energy and therefore in total energy when you raise the tennis ball from the desk to above your head. Toss the tennis ball in the air, against a wall, or bounce it on the floor. Discuss the increase in kinetic energy during these activities. Discuss ways you can increase the internal energy of the ball (putting it in a microwave vs. bouncing it on the floor). Students should be able to identify the three different forms of internal energy.

Additional Application: Conservation of energy. When bouncing the ball against the floor, a change in kinetic and internal energy occurs. On the way down, there is a decrease in potential energy and a corresponding increase in kinetic energy. On the way up, the ball decelerates and trades kinetic energy for potential energy. If the ball bounces enough times (i.e. during a tennis match), the ball warms up. This is an increase in internal energy. Because the collisions between the floor and the ball are not perfectly elastic, there are losses associated with each impact. The conservation of energy states that the total energy must not change during this process, so the loss of kinetic energy after the collision must be compensated by a corresponding increase in internal energy. The losses associated with each bounce can also lead to a discussion of the second law in terms of an increase of entropy in the system. The ball does not return to the exact height from which we released it. The decrement in height is associated with frictional losses and the internal losses from the elastic stretching of the polymer strands in the rubber.

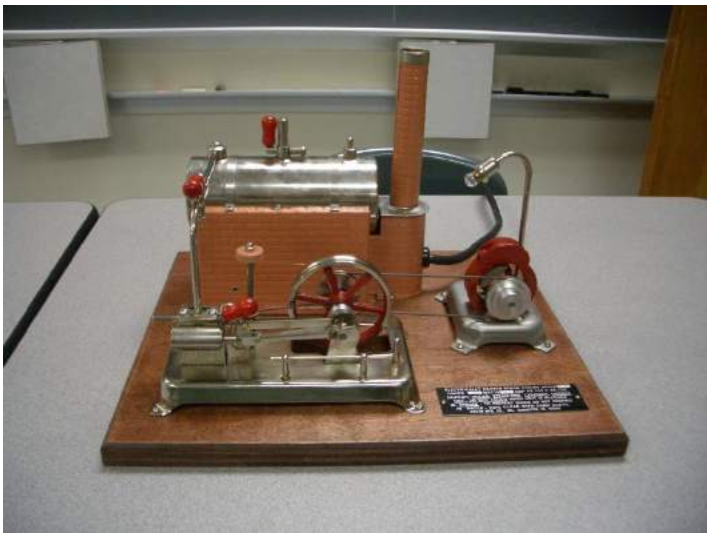
THE LITTLE ENGINE THAT COULD – THE VAPOR POWER CYCLE

THERMODYNAMICS

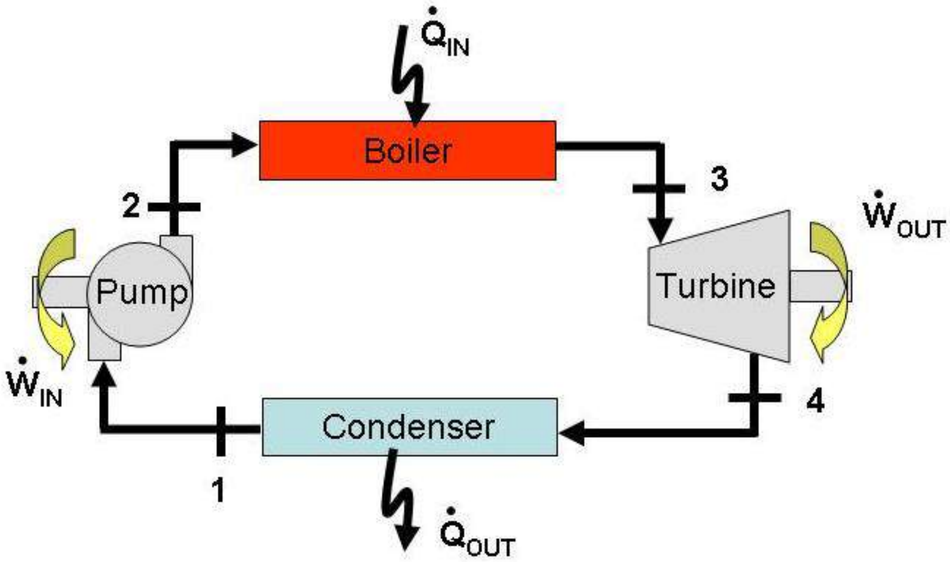
Keywords: Rankine Cycle, Steam, Vapor Power Cycle

Submitted by: Phil Root

Model Description: This is a demonstration of the fundamentals of the vapor power cycle in that it translates the internal energy of steam into mechanical then electrical power. This demonstration falls short of demonstrating the true vapor power cycle in that the steam is not returned to the boiler; instead it is vented as exhaust. This demonstration should take 10-15 minutes.



Engineering Principle: The Rankine cycle seeks to transfer thermal energy into mechanical energy. The basic components necessary for a Rankine cycle are highlighted below.



Starting at point 1 where the liquid water emerges from the condenser, the pump increases the pressure to point 2. The boiler transfers a great deal of thermal energy into the liquid causing a large increase in enthalpy and a phase change to superheated vapor. The turbine uses this high enthalpy at the inlet (state 3) to turn the turbine blades and produce work. The vapor at state 4 then passes through the condenser returning the fluid to a liquid.

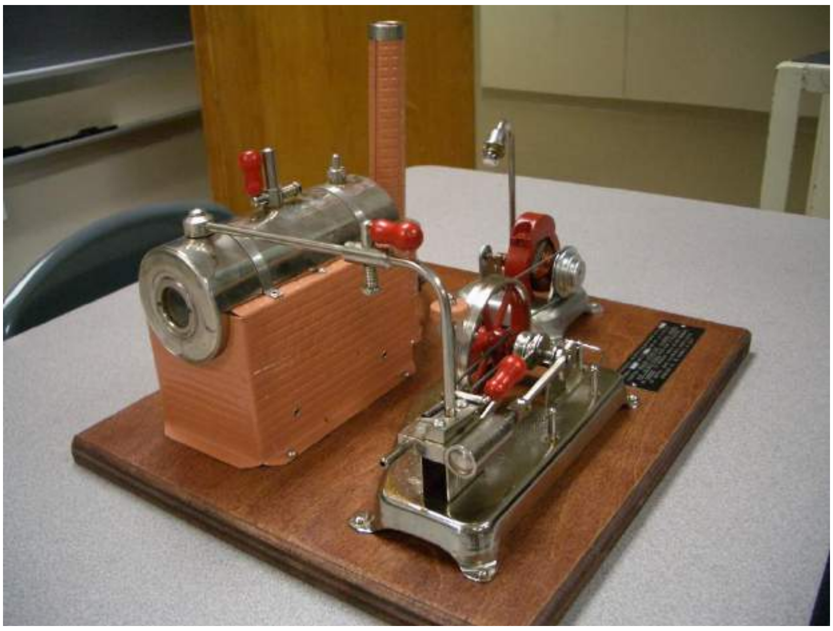
In this demonstration, there is no condenser or pump. The water in the reservoir is heated to the point of steam and travels from the boiler through the piston cylinder device. After creating work out of the system, the steam vents as exhaust. Once the reservoir is empty the steam engine can no longer produce work. This is sufficient however to demonstrate the conversion of thermal energy into mechanical work and then electrical work.

REQUIRED ITEMS

Item	Qty	Cost and Build Time	Description/Details
Steam Engine	1	$600-750	Not widely available. Jensen Manufacturing (www.jensensteamengines.com) and Wilesco (www.wilesco-steam.co.uk) have a large selection of hobby and educational steam engines. Several other vendors offer similar products such as Midwest Products (www.midwestproducts.com). Recommend purchasing a steam engine that is electrically heated as compared to powered by dry fuel (i.e. Sterno).

APPLICATION

Before Class: Fill up the water reservoir. Plug in the device to allow it time for the boiler to create steam. This process can take up to ten minutes so plan accordingly. Have paper towels ready to clean up the steam exhaust. Some of these steam engines will allow you to boil the water but not release it to the piston until you are ready for the demo.



In Class: Open the valve to allow the flow of steam to the piston and flywheel. It may require that you spin the flywheel to get it started. After the flywheel is moving the piston will convert the thermal energy from the steam into the mechanical energy required to move the piston and turn the flywheel.

Observations: Students should be able to visualize the conversion of energy from electrical energy required to heat the water to thermal energy required to move the piston to mechanical energy required to turn the flywheel.

Additional Application: Several of these devices are connected to a light bulb via an electric generator to further illustrate the conversion of mechanical energy to electrical energy.

If you unplug the steam engine, the thermal energy stored in the steam is still sufficient to power the piston for several more minutes. Discuss why.

The speed of the piston and flywheel increases if you disconnect the light bulb. Discuss why.