The Video Encyclopedia *of* Physics Demonstrations™

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D I S C   F O U R

Chapter 10 *Statics*

Chapter 10

STATICS

Force Board

A "Force Board" allows us to investigate the conditions for equilibrium of three or more forces.† In this case, three forces are at equilibrium, as indicated by the stability of the center ring on which they are acting, as shown in *Figure 1*. Components of each of the three forces along the *x* and *y* axes are graphed, clearly showing why the system is in equilibrium.

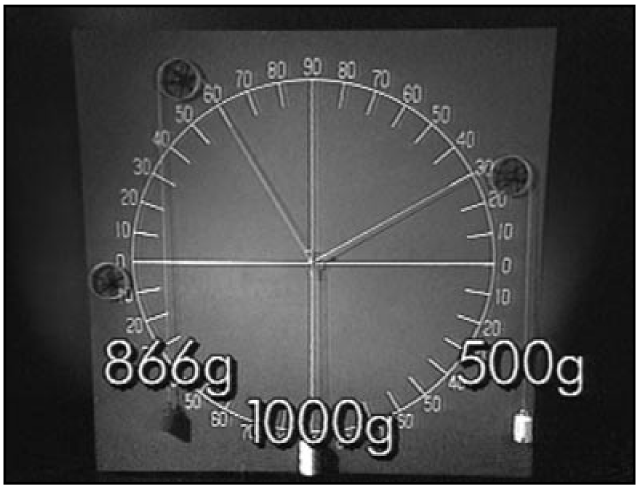

Figure 1

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-12.

The strings tied to this ring exert forces on the ring. Masses hanging from the ends of the strings provide the actual force; a 500-gram mass on this string, an 866-gram mass on this string and a 1000-gram mass on this string.

If we pull the ring away from the center, it returns to its original position. The ring is in stable equilibrium.

These vector arrows represent the force exerted by this string and the components of that force in the horizontal and vertical directions.

Here is a similar analysis for the second string.

The horizontal components of the two forces are already in balance.

The third weight must equal the sum of the two vertical components

or 9.8 newtons.

Equipment

1. Vertically supported board to support three or more pulleys and a temporary stability peg (positioned in the center which can be either pulled out to hold the center ring or pushed in so the center ring is free to move). It helps if the angular position of the pulleys is clearly marked on the board.
2. Center ring with three lengths of string tied to it, with a loop tied at each of the other ends.
3. Three weights with hooks (we used 500, 866 and 1000-gms.).

Demo 04-02 Clothesline

If a weight, such as an item of clothing, is hung from the center of a long clothesline, the clothesline sags.[†] It requires an infinite force to fully straighten out the clothesline. When the tension in the clothesline and the vertical components of that tension are drawn, as in *Figure 1*, it becomes clear why a large force (theoretically infinite!) is required to straighten out the line.

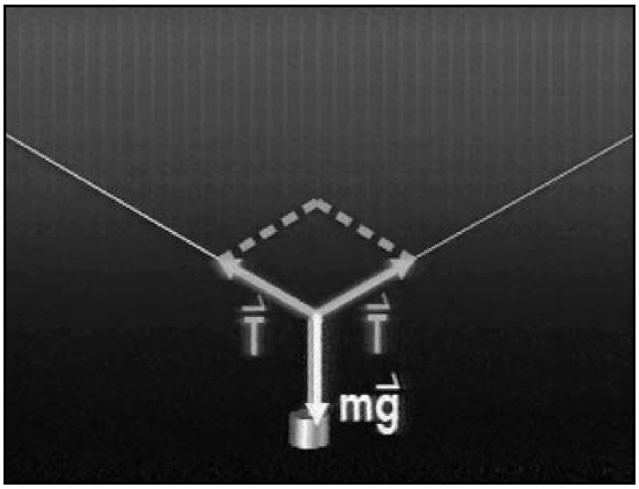

Figure 1

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-13.

When a piece of clothing is hung on a clothesline, the clothesline always droops.

This mass has a weight of about 5 newtons, as shown by this spring scale. If we attach the spring scale to one end of the line and then hang the mass in the center, how much force will have to be applied to completely straighten the line? 5 newtons? 10 newtons? Or more?

Even 50 newtons will not completely straighten the line. The force required to get the line perfectly straight is infinitely large.

This animation shows the gravitational force pulling down on the hanging mass, and the tension forces in the rope as the tension is increased. For the system to be in equilibrium, the sum of the two tension forces must be equal but opposite to the gravitational force on the hanging mass.

Equipment

1. Length of light rope or heavy cord.
2. Spring scale.
3. Weight.
4. Support for one end of clothesline.

Demo 04-03 Load on Removable Incline

A small cart is held in place on an inclined plane by means of a mass hanging over a pulley. If another force is applied to the cart at an angle with respect to the incline, the cart will move until the force is exactly perpendicular to the incline, as shown in *Figure 1*. If the magnitude of the upward force is then increased until it is exactly equal to the normal force, the incline can be removed and the cart will remain suspended in space.†

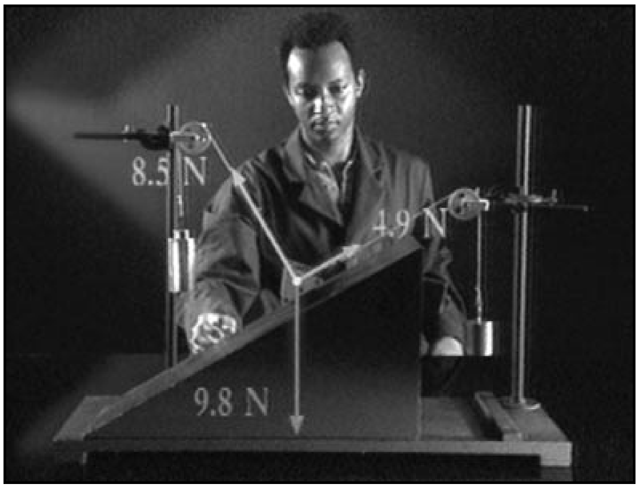

Figure 1

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-18, Car on Inclined Plane. Freier and Anderson, *A Demonstration Handbook for Physics,* Demonstration Mj-2, Forces on an Inclined Plane.

This cart on an incline is acted on by three forces: A downward gravitational force,

a force along the direction of the incline supplied by this weight and string, and a force perpendicular to the incline provided by the incline itself.

A mass hanging over this pulley will provide a force equal to the force from the incline.

At this point, do we need the incline?

The incline is no longer needed. It can be removed and the cart will stay in place.

Equipment

1. A 30° incline plane (self-contained so it is free to move).
2. A rolling body.
3. Two pulleys, two clamps, and two ring stands.
4. Two weights of appropriate size to counter balance the components of the body's weight.

Demo 04-04 Pulley Advantage

A pulley is arranged as shown in *Figure 1*, so that a mechanical advantage is obtained in lifting a heavy weight.† The price paid for reduction in the force required is that the force must be applied over a longer distance, as mentioned in the video, because the work required to lift the weight the same vertical distance is the same in any case.

Figure 1

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-45.

Pulleys have two main purposes: changing the direction of a force and reducing the force needed to lift an object through mechanical advantage.

This metal cylinder has a weight of about 10 newtons. If we hang the weight on a string passing over this pulley,

it still requires 10 newtons to lift the weight. The direction of the force is changed, but its magnitude remains the same.

If we hook the end of the string to a fixed point and hang the weight from this free-running pulley,

only 5 newtons are required to lift the weight. But the weight being lifted only travels half as far as the scale doing the lifting.

Equipment

1. Tall ring stand.
2. Pulley.
3. Clamp.
4. Hook.
5. Mass.
6. Spring scale.
7. Length of string with loops at both ends.

Demo 04-05 Pulley and Scales

The setup shown in *Figure 1* is used as a question for the student to check his or her understanding of how a pulley works.† A pulley and a spring scale connected as indicated are mounted in a frame that in turn hangs from an upper spring scale. The weight of the frame and its contents is 5 N, as read from the upper spring scale. When the free end of the rope is pulled, until the lower spring scale reads 10 N, what will the upper spring scale read? (The answer is 10 N).

The reason for this seemingly counterintuitive behavior lies in the way a pulley works. Although a force of only 5 N is exerted down by pulling the rope, the same tension of 5 N exists on both sides of the pulley, so that the fixed end of the spring scale must feel a 10-N downward force. However, the fixed end of the string is pulling up on the frame with the same 5-N force, so the net downward force exerted on the upper scale by pulling the end of the rope is only 5 N.

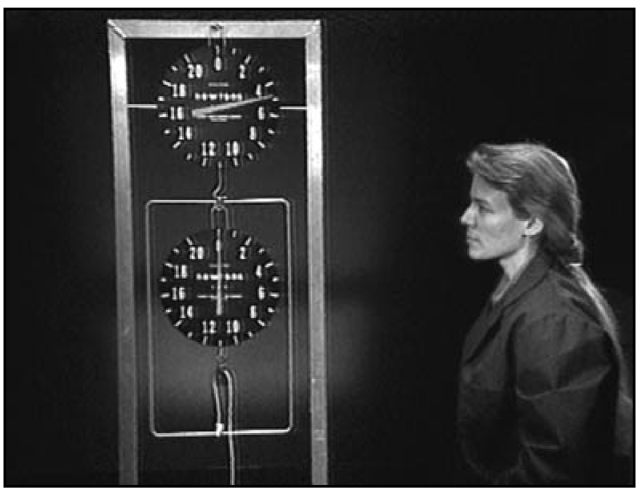

Figure 1

† Richard M. Sutton, Some Stepped-Up Lecture Table Experiments, *Am. J. Phys.* 10, 141-145 (1942).
A Capecelatro, Harry Meiners, Joseph Pizzo, and Carolyn Sumners, *The Spring Balance Reads Less Than Expected*, Exhibit #6 at the Frank Oppenheimer Memorial Exhibit, The Exploratorium, San Francisco, Winter 1987 Meeting of the American Association of Physics Teachers.

Pulley and Scales / Script

We use this system of spring scales to illustrate one aspect of how a pulley works.

The lower spring scale hangs from the top of this frame with a pulley hanging from the bottom of the scale. A rope attached to the bottom of the frame passes over the pulley and hangs freely.

If the free end is gently pulled, a force is exerted on the spring scale. The frame is then suspended from the upper spring scale; the weight of the frame system is about 5 newtons. If the free end of the rope passing over the pulley is gently pulled until the lower scale reads 10 newtons, what will the upper scale read, 5, 10, or 15 newtons?

Why do we get this surprising result? Because the pulley is attached directly to the lower scale it doubles the force in that scale but has no effect on the upper scale to which it is not attached.

Equipment

1. Rectangular frame that supports a spring scale and a pulley from its top and from which a cord is tied and then runs up through the pulley and downward below the frame.
2. Larger rectangular frame that supports a second spring scale, which in turn supports the assembly in number one.

Demo 04-06 Simple Machines

This demonstration illustrates some simple machines: the inclined plane, the lever, the screw jack, and the block and tackle. It shows how a relatively small force can be used with these simple machines to lift a large weight.

Figure 1

Devices which make it possible to lift a mass using a force smaller than the force required to lift it directly are known as simple machines.

This spring scale measures the force needed to lift a wooden block directly.

An inclined plane makes it possible to raise the block using a smaller force.

This lever makes it easy to lift a heavy iron weight using one hand.

The incline of the threads on this screw jack also reduces the force necessary to raise the weight.

This set of pulleys, known as a block and tackle, also allows a weight to be lifted using a reduced force.

Equipment

1. Inclined plane.
2. Spring scale.
3. Block with hook.
4. Heavy weight.
5. Stiff bar.
6. Pivot.
7. Screw jack.
8. Block and tackle.
9. Clamped down tall ring stand.

Demo 04-07 Levers

The three classes of levers are illustrated, as in *Figures 1* through *3*, respectively.[†] In each case, the force required to lift the weight is measured for several lever-arm positions.

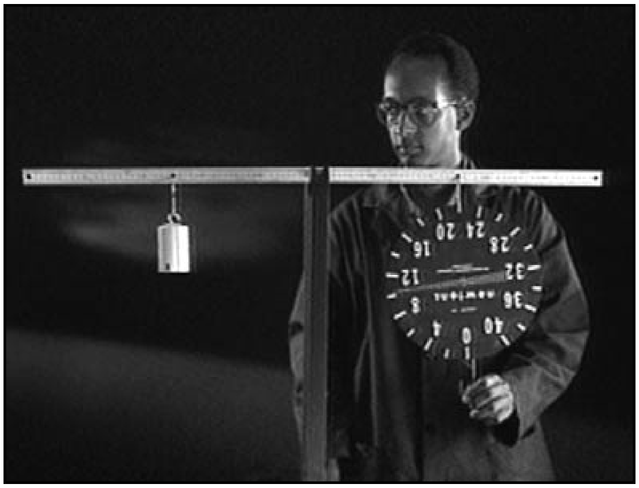

Figure 1

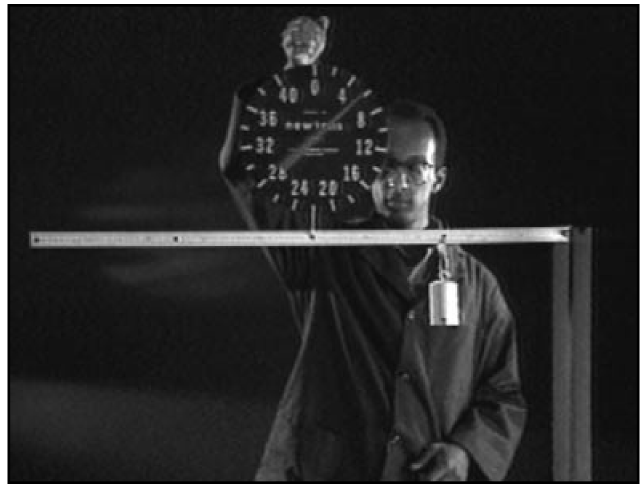

Figure 2

Figure 3

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-43, Lever.

We'll use this meter stick and a fulcrum to construct three kinds of levers.

Here is a setup known as a class I lever, where the weight and the force are on opposite sides of the fulcrum.

Notice how the force needed to balance the lever changes with the distance from the fulcrum.

This is a class II lever, where the weight is between the fulcrum and the lifting force.

This is a class III lever, where the lifting force is between the fulcrum and the weight.

Equipment

1. Tall ring stand.
2. Pivot system.
3. Meter stick with holes in desired position.
4. Spring scale.
5. Weight.

Demo 04-08 Horizontal Boom

This demonstration investigates the forces developed in two types of boom structures, shown in *Figures 1* and *2*. For each case, the tension in the wire is measured for various load weights.

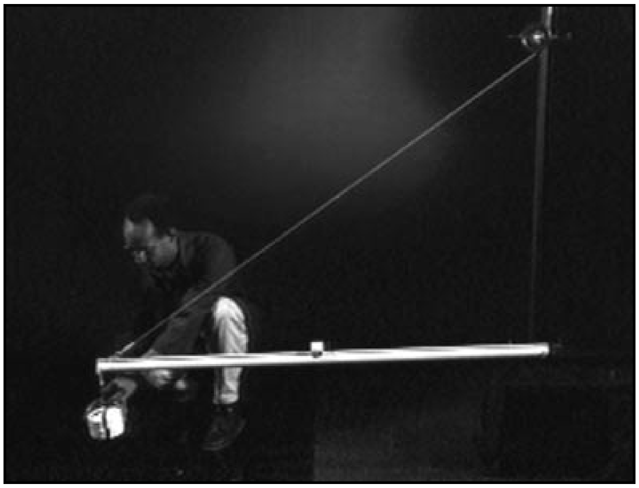

Figure 1

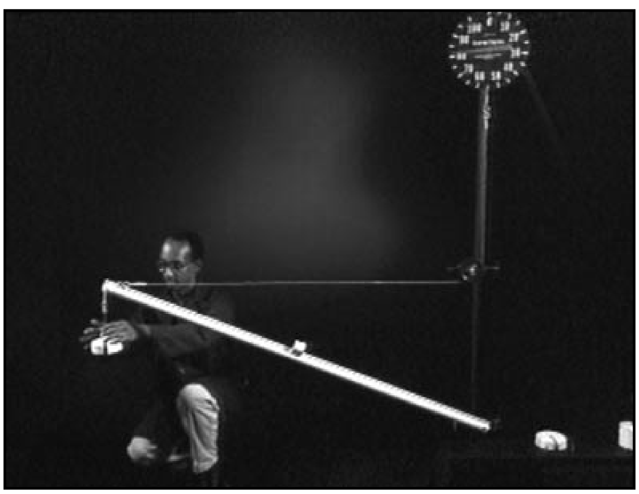

Figure 2

This boom arm is supported by a wire that is attached to a spring scale.

The scale shows the tension which is necessary to support the arm. The arm has a mass of about 2.2 kilograms.

Now we'll add 2 kilograms to the arm.

Here is the new reading on the scale.

Now we'll put 4 kilograms on the arm.

Here is the new reading.

Now we'll move the pulley holding the wire to a new position. Here is the reading on the scale with the arm empty.

Here is the reading with 2 kilograms added.

Equipment

1. Very tall support rod which can be clamped down securely.
2. Hook.
3. Spring scale.
4. Pulley and clamp.
5. Length of wire or cable.
6. Boom rod with pivot on one end attached to number 1, and an attachment system on the other end for number 5.
7. Weight hanger.
8. Slotted weights.

Demo 04-09 Arm Model

An arm model, shown in *Figure 1*, is used to illustrate the forces and torques created by the biceps and the triceps muscles. A ball is thrown, illustrating the action of the muscles in a dynamic situation.

Figure 1

Here is a simplified model of the human arm.

The muscles of the upper arm are represented by ropes which attach to opposite sides of the elbow joint. Pulling on the ropes works the lower arm like a lever. The rope representing the biceps muscle pulls the arm in by exerting a force at this point, while the rope representing the triceps muscle pulls on the opposite side of the elbow and opens the arm.

With a rapid pull on the triceps rope, the model arm can throw a ball.

Equipment

1. Support system.
2. Two lengths of tubing joined so the end of one can pivot about the end of the other. This assembly has one far end firmly fixed to the support system, while the other far end has a cup-like attachment that serves as a hand.
3. Two lengths of rope attached to the lower arm on each side of the “elbow joint” and then passing through eye screws attached to the upper arm.

Demo 04-10 Torque Bar

A torque bar, illustrated in *Figure 1*, is used to illustrate the concept of torque in a dramatic way.† As a weight is suspended further out along the bar, it requires an increasingly greater torque on the handle to lift the weight, as the expression on the demonstrator's face in *Figure 2* indicates.

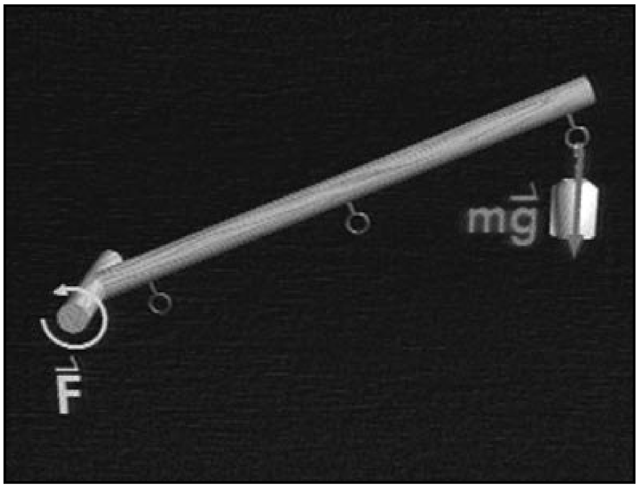

Figure 1

Figure 2

† Freier and Anderson, *A Demonstration Handbook for Physics,* Demonstration Mo-5, Grip Bar.

This wood T-bar has eye hooks at regular intervals along its length. If we hang a one kilogram weight on this hook, a person can easily lift the weight off the table with a twist of the wrist.

When the weight is hung on the middle hook, it becomes more difficult to lift.

If we place the weight on this hook, it becomes very difficult for a person to hold up the bar.

This animation shows the force due to the hanging weight, and the magnitude of the twisting force which is needed to support the bar.

Equipment

1. Sizable dowel rod cut and attached in the form of the letter T, with eye screws attached at 10-cm intervals along the long rod, starting 10 cm from the handle.
2. One to two-kilogram weight.

Demo 04-11 Hinge Board

A “hinge board,” shown in *Figure 1*, is used to illustrate the concept of torque. A greater force is required to rotate the board about its hinge (on the left side) when the force is applied closer to the hinge. This is one reason why doorknobs are found on the side of the door opposite the hinges.

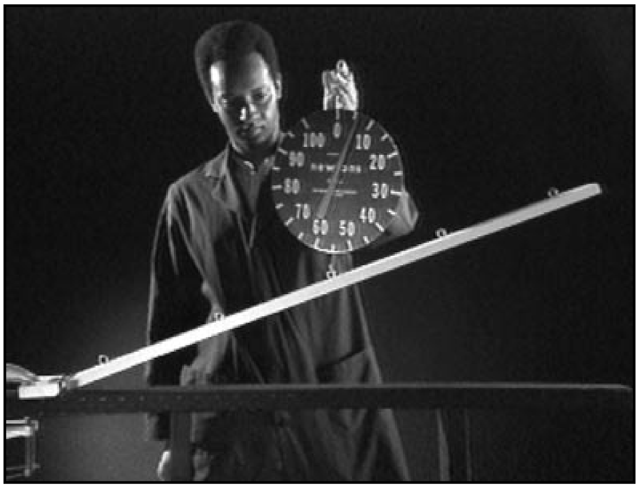

Figure 1

Why are the doorknobs put on the outer edge of doors instead of in the middle?

This hinge board will show the reason.

The board tilts up on a hinge, and may be lifted by pulling up on any of these eye hooks along its length.

If we pull up on the eye hook with a spring scale to measure the force needed to lift the board in each case, which eye hook will require the greatest force?

The inner hook takes the greatest force to lift the board. Heavy doors are easiest to move if the handle is on the edge furthest from the hinge.

Equipment

1. Hinge board—made by fastening a longer board (with hooks spaced along its length) to a shorter board (for clamping purposes) with a hinge.
2. Spring scale.

Demo 04-12 Torque Wrench

A torque wrench is used to illustrate the concept of torque and how torque is applied to the head of a screw. The difference in the strength of aluminum and steel screws is illustrated. *Figure 1* shows graphics of the mechanism of a torque wrench. Torque wrenches are used to avoid exceeding the breaking strength of bolts.

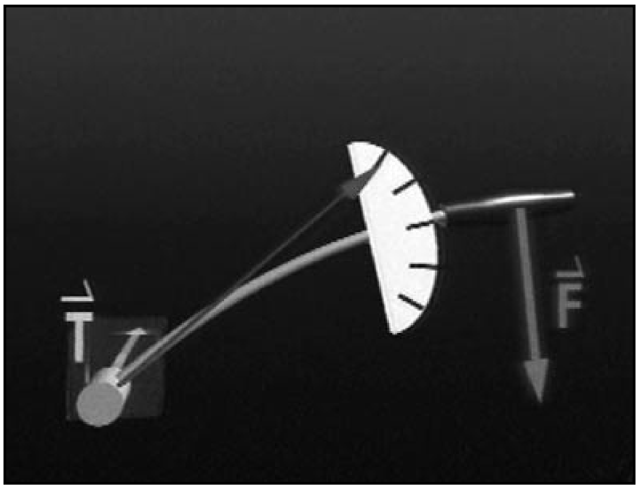

Figure 1

This torque wrench will be used to demonstrate torque measurement and shear strength of bolts.

When the wrench is placed on this bolt and the handle turned, a torque is exerted on the bolt.

The force producing the torque bends the shaft of the wrench slightly, with the amount of bend readable from this pointer and scale.

Let's apply some torque to this aluminum bolt and see what happens.

The bolt breaks under only a small torque.

Let's try this bolt, which is made of hardened steel for greater strength.

It takes a larger torque to break the stronger bolt.

This animation shows the forces that act on the wrench, and the resultant torque on the bolt.

Equipment

1. A block of metal that has been drilled and tapped several times and securely clamped down.
2. Torque wrench.
3. Supply of bolts matching the threads of number 1 with differing physical properties.

Demo 04-13 Torque Wheel

A "torque wheel," shown in *Figure 1*, is used to illustrate static equilibrium of torques.† Various combinations of weights are applied at various radius values on the torque wheel to obtain static equilibrium of torques.

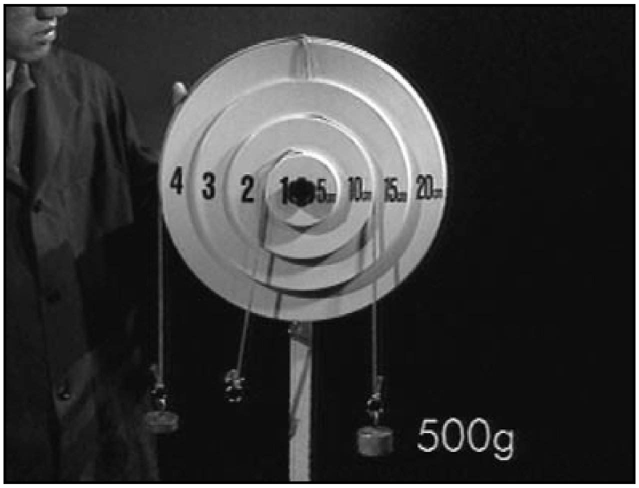

Figure 1

† Freier and Anderson, *A Demonstration Handbook for Physics,* Demonstration Mo-2, Force Disc.

We'll use this torque wheel to demonstrate the addition of torques to produce rotational equilibrium.

The wheel has discs of different diameters around which ropes can be wound, with no weights hanging from the ropes the wheel is stable.

If a single 1000-gram mass is hung from the 5-centimeter diameter disc, the wheel is unstable and begins to rotate.

How much weight should we hang from the 10-centimeter disc to balance the wheel?

A 500-gram mass rebalances the wheel.

If we remove the 1000-gram mass from the wheel, how much mass should we hang from the 20-centimeter disc to balance the wheel?

250 grams balances the wheel.

Equipment

1. Commercially available torque wheel.
2. Several hooked weights.

Demo 04-14 Balancing Meter Stick

A meter stick suspended at its center is used as a torque balance, as shown in *Figure 1*.† Balance is maintained by placing various weights at appropriate positions on both sides of the fulcrum.

Figure 1

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-27.
Freier and Anderson, *A Demonstration Handbook for Physics,* Demonstration Mo-1, Loaded Beam.

This meter stick is free to rotate on a pivot point at its center. Pegs at three different distances from the center can hold masses of either 100, 150, or 300 grams. If we put a 300-gram mass on this first peg, the stick becomes unbalanced.

We can rebalance the stick by placing another 300-gram mass on the corresponding peg on the other side.

To balance the stick, where should we put a 150-gram mass?

We put it twice as far from the center as the 300-gram mass. Now we remove the 150-gram mass. Where should we place a 100-gram mass to balance the stick?

We put it three times as far from the center as the 300-gram mass.

Equipment

1. Ring stand and clamps.
2. Meter stick with low friction pivot at its center and support rods at desired points of interest.
3. Several weights with holes in their centers for ease of hanging from the rods mentioned in number 2.

Demo 04-15 Meter Stick on Fingers

A meter stick is balanced on two fingers, as shown in *Figure 1*, with one finger at one end of the meter stick and the other finger about one-quarter of the way from the other end. Which side, if either, will the meter stick fall from when the two fingers are slowly brought together?† This experiment is carried out under several conditions, changing the friction between the finger and the meter stick.

When this experiment is performed, the finger closer to the center of mass of the meter stick (including any added weights) supports more weight, so it experiences a higher frictional force, and the other finger slides. This condition may reverse several times, but eventually both fingers will meet under the center of mass!

Figure 1

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-50, Dependence of Friction on Pressure.

Here's an interesting puzzle.

If a person balances a meter stick on two fingers, with one finger closer to the end of the stick than the other, and then slides both fingers in toward the center, which side will the meter stick fall toward, if it becomes unbalanced?

The meter stick stays balanced the entire time, and both fingers end up exactly at the middle. Let's watch that again with one of the fingers starting even closer to the center.

Again the stick stays balanced.

But if we try to reverse the process, the stick falls off.

If we cover one finger with a rubber glove and coat the other with slippery chalk dust, will the meter stick give up this time and become unbalanced?

Even with such a large difference in friction, the stick stays balanced.

If a weight is added to one end of the meter stick and the demonstration is repeated,

the stick still remains balanced, but the fingers meet at a different spot.

Equipment

1. Meter stick.
2. Rubber glove.
3. Supply of chalk dust.
4. Weight and circle of tape to temporarily attach weight to the meter stick.

Demo 04-16 Bridge and Truck

As a truck crosses a single span bridge, as shown in *Figure 1*, how does the downward force on each of the two piers change?† This force is measured as the truck is moved across the bridge. As the truck moves across the bridge, the equilibrium of torques condition requires that the force required to support the truck is greater at the tower closer to the truck, as shown in the video.

Figure 1

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-23, Bridge and Truck Problem.
Freier and Anderson, *A Demonstration Handbook for Physics,* Demonstration Mo-7, Loaded Beam.

Do the forces supporting the ends of a bridge change as a heavy bus moves along the bridge, or are they always the same?

This demonstration uses a model bridge supported by spring scales and a heavy toy truck to find out.

When the bridge is empty, both scales supply the same force to support their end of the bridge.

If the truck is placed in the middle of the bridge, the scale readings increase but are still equal.

What if the truck is now moved to the right? Will the scales still show the same reading?

The force provided by the right scale increases and the force from the left scale decreases.

As we move the truck closer to the end, the difference continues to increase.

Equipment

1. Two platform spring scales.
2. Board or model of bridge.
3. Loaded toy truck.

Demo 04-17 Roberval Balance

A Roberval balance,[†] shown in *Figure 1*, is a type of torque balance. The unusual mechanism is designed so that the system is in neutral equilibrium with identical weights at *any* position along each of the platforms, as shown in the video.

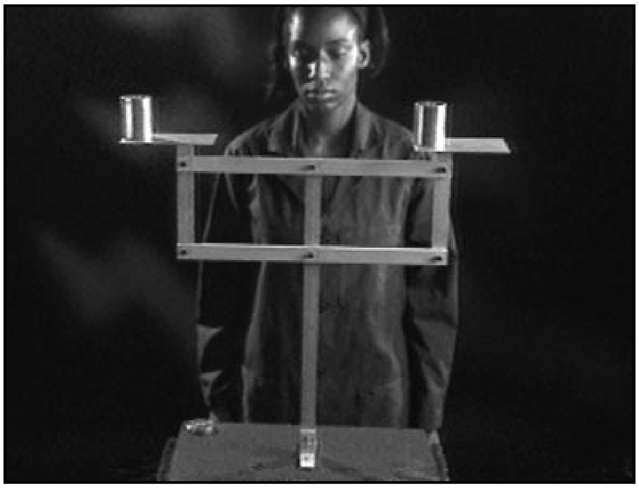

Figure 1

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-41, Balance.
Freier and Anderson, *A Demonstration Handbook for Physics,* Demonstration Mo-6, Torque Independent of Lever Arm.

When a pivoted bar is used as a balance to compare two weights, one must be very careful to set both weights at the same distance from the pivot, otherwise even two equal weights such as these will not balance the bar.

Here is a special type of balance, known as a Roberval balance, which eliminates the problem of weight placement.

Equal weights can be placed anywhere on the trays,

and they will always balance.

Only unequal weights will unbalance the scale.

Equipment

1. Roberval balance designed so that its lower cross arm can be removed, allowing it to be utilized as a standard equal arm balance or as a Roberval balance.
2. Two equal weights.
3. Small third weight.

Demo 04-18 Ladder Forces

When a ladder is leaned against a wall, as shown in *Figure 1*, several forces are exerted on the ladder by the wall and the floor.† The forces depend on the angle of the ladder, as shown in the video.

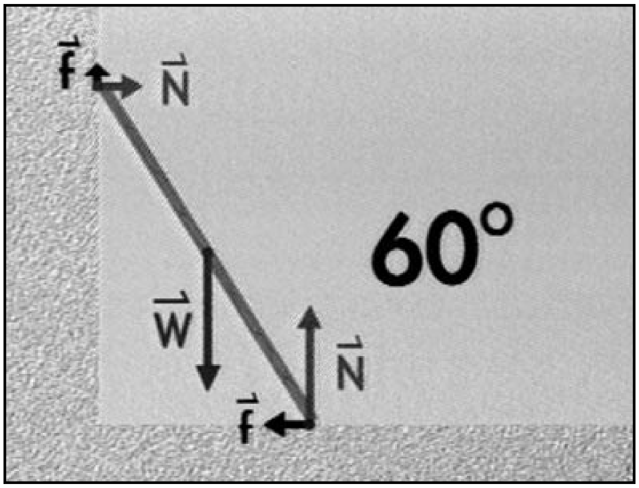

Figure 1

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-30.
Freier and Anderson, *A Demonstration Handbook for Physics,* Demonstration Mo-8, Forces on a Ladder.

This 10-kilogram ladder is leaning against a wall at a small angle to the vertical.

This diagram shows the forces acting on the ladder: the gravitational force, the normal and frictional forces from the ground, and the normal and frictional forces from the wall.

This animation shows how the forces change as the ladder is moved.

Equipment

1. Ladder.
2. Clear wall.
3. Smooth floor.

Demo 04-19 Broom Stand

A broom will normally tip over if you try to stand it on its bristle end. However, if you spread out the bristles the broom can be made to balance, and will stand on its bristle end, as illustrated in *Figure 1*.

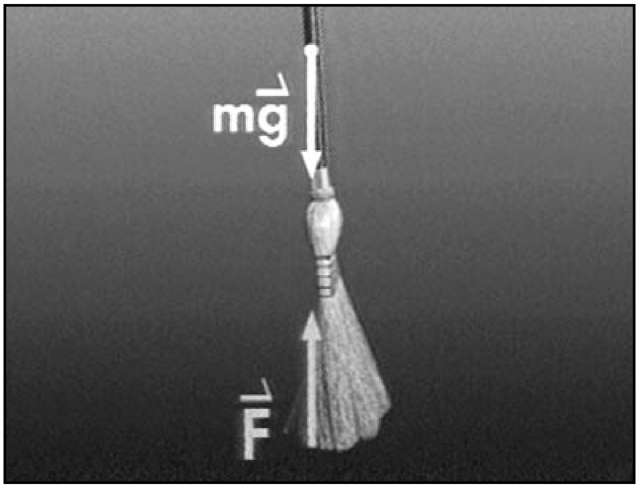

Figure 1

We all know that tall thin objects are unstable when stood on end. This broom falls over quickly when left alone.

But if we spread the bristles out slightly so that the broom stands on a wide base, it will stand on its own even when it is tipped away from being vertical.

This diagram shows the forces which act on the broom in this position.

Equipment

Ordinary straw broom (a new one with squarely cut bristles works best).

Demo 04-20 Bed of Nails

The traditional bed of nails, this one containing about 7000 nails, is used to illustrate the distribution of weight. A subject lies on his back on the bed of nails, with a concrete block on his chest. The concrete block is then smashed using a heavy sledge hammer, without damage to the skin of the subject lying on the bed of nails.

Because there is a very large number of nails supporting the subject, the force exerted by any one nail is insufficient to damage the clothing or skin of the subject.

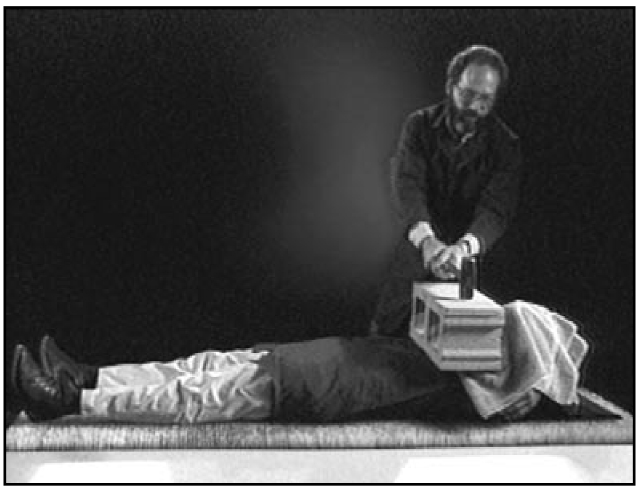

Figure 1

† Freier and Anderson, *A Demonstration Handbook for Physics,* Demonstration Mv-2, Power.

Perhaps you've heard of the magician's trick of lying on a bed of nails without harm. We'll use this bed of nails to show that it is physics, not magic, that does the trick.

This bed contains 7000 nails, which produce a large enough total surface area that a person may lie down on the bed without worrying about a puncture from any one nail.

To drive the point home, we'll place this large concrete block on the person's chest and smash it with a hammer.

Even the extra force of the hammer blow on the block is not enough for any of the nails to puncture the skin.

Equipment

1. Bed of nails (#8 penny nails on half-inch centers).
2. Pillow for head.
3. Towel or face shield.
4. Concrete building block.
5. Heavy hammer.
6. Willing assistant.

Demo 04-21 Egg Crusher

A raw egg is squeezed between two hard foam rubber pads in an "egg crusher." Because the force is distributed over a large area of the end of the egg, as shown in *Figure 1,* and because the shape of the egg is a type of arch, and has enormous strength, a force of over 150 pounds can be placed on the egg.

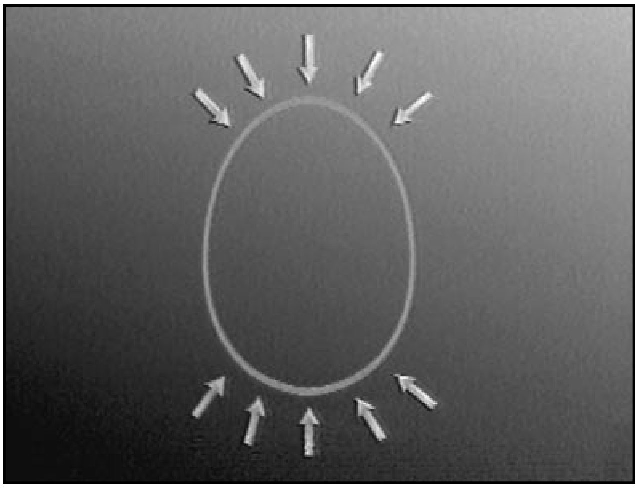

Figure 1

Everyone knows that an egg is fragile.

We will now use this egg crusher to apply a large force to an egg.

The egg crusher consists of an aluminum tube and plunger, each having a layer of hard but flexible foam rubber. Placing the egg between the two layers of hard foam rubber, it will be squeezed by placing the same 25-pound lead brick onto the platform and then adding additional lead bricks one at a time.

75 pounds.

100 pounds.

125 pounds.

150 pounds.

The egg does not break because the hard but flexible foam rubber distributes the weight over a larger area of the shell.

Equipment

1. Egg crusher.*
2. Supply of raw eggs.
3. Supply of lead bricks.
4. Skillet.

* Built from two concentric cylinders: a hollow one having "windows" in its lower half and welded to a substantial base with its lowest portion equipped with a piece of thick hard foam rubber, the second cylinder, which slides inside the first, is equipped with another hard rubber pad on one end and an end plate to support the bricks on the other.