The Video Encyclopedia *of* Physics Demonstrations™

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DISC TWO

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Chapter 5 *Inertia*

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CHAPTER 4

MOTION
IN A PLANE

Demo 02-01 Shooter / Dropper

This demonstration illustrates the independence of velocity components by showing that accelerated motion along a vertical line is independent of horizontal motion.

A ball is released from rest at the same time that a second identical ball is projected horizontally from the same vertical height, as indicated in *Figure 1*.[†] The question is how they fall, whether either of the two will reach a horizontal surface before the other, or whether they will reach the surface at the same time. Because of the independence of horizontal and vertical components of the motion, the two balls will fall with the same acceleration, the acceleration of gravity. This means that they will at all times move together vertically and at any time they will be at the same vertical height, which is clearly shown on the video.

Figure 1

[†] Sutton, *Demonstration Experiments in Physics*, Demonstration M-91, Rate of Fall Independent of Horizontal Motion.
Freier and Anderson, *A Demonstration Handbook for Physics,* Demonstration Mb-14, Simultaneous Fall.

Shooter / Dropper / Script

Demo 02-01

How is the vertical motion of a falling ball affected by its horizontal motion? We'll use this device to find out.

If a ball is loaded onto the back and the trigger is pulled, the ball falls straight down.

If another ball is loaded on the front and the trigger is pulled, the ball both flies horizontally and falls vertically. But how do the vertical accelerations of these two falling balls compare? If we drop one ball vertically at the same time we fire the other horizontally, which will strike the ground first?

They both strike at the same time. The vertical acceleration of a falling ball is unaffected by its horizontal motion.

Equipment

1. Spring-loaded gun designed to simultaneously shoot (horizonatally) and drop (vertically) two balls.
2. Two billiard balls drilled through their centers to accommodate the spring-loaded shaft.
3. Support system for gun.

Demo 02-02 Monkey Gun

This is an extension of the shooter/dropper demonstration. A projectile is aimed at a bottle and shot at it at the same time that the bottle is released from rest, as indicated in *Figure 1*.[†] Because the projectile was aimed at the bottle, in the absence of gravity it would move along a straight line and strike the bottle.

The acceleration of gravity acts on both the projectile and the bottle. In the time that the projectile takes to move to the vertical line directly under the bottle, the projectile has "fallen" the same distance away from the line it would follow in zero-gravity as the bottle has fallen from the magnet. Since that is always true, when they reach the same horizontal position they must collide.

This illustrates that the horizontal and vertical velocity components are independent and that the acceleration of gravity acts on both objects equally independent of their initial states of motion.

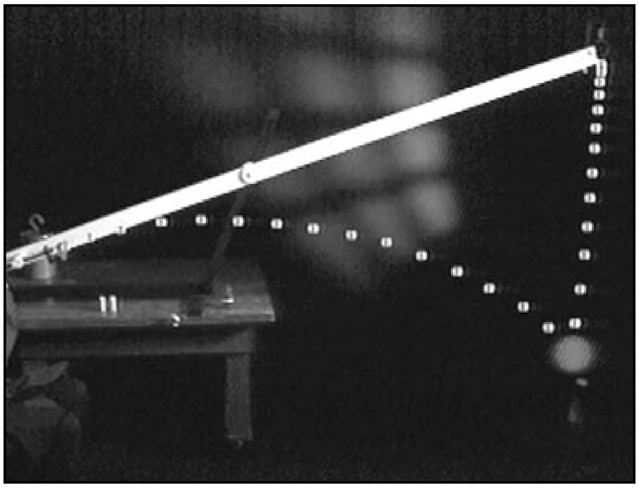

Figure 1

[†] Sutton, *Demonstration Experiments in Physics*, Demonstration M-92, Falling Target.
Meiners, *Physics Demonstration Experiments*, Sec. 7-2.20, "Monkey-and-hunter" demonstration, p. 130.

This brass tube points directly at a plastic bottle hanging from an electromagnet. If we put a wooden dowel in the tube and blow into the tube, the dowel is fired straight at the hanging bottle.

But as the dowel flies out of the tube, it knocks off a piece of aluminum foil carrying current to the electromagnet.

The electromagnet shuts off, and the bottle begins to fall just as the dowel flies out of the tube.

Even though the bottle is no longer in the spot at which the dowel was aimed, the dowel still strikes the bottle. Here is a repeat with the dowel fired at a lower speed.

These dots will track the positions of the dowel and the bottle at one-tenth of a second intervals as the last sequence is repeated.

Equipment

1. Blow gun with a release mechanism. Our release is a support to hold a strip of aluminum foil where its position is at just the point where the projectile begins its fall. The foil is actually part of the series circuit that supplies the electromagnet which initially holds the target. When the projectile pushes the foil away, both the projectile and the target begin their fall at the same instant.
2. Projectile (dowel rod).
3. Target (plastic bottle containing some lead shot—keeps bottle from tumbling).
4. Electromagnet (in series with the release mechanism and an adjustable line resistor set to still hold the target while minimizing the hysteresis effect).

Demo 02-03 Vertical Gun on Car

This demonstration illustrates the independence of velocity components.

A car rolls horizontally with a constant velocity. While the car is rolling, a ball is shot vertically from a funnel on the car. The ball moves in a parabolic arc, remaining directly above the funnel at all times, and falls back into the funnel, as illustrated in *Figure 1*.[†] The only condition required for this demonstration to work is that the car continue to move at a constant speed in a straight line, so the horizontal velocity component of both the car and the ball remains the same at all times.

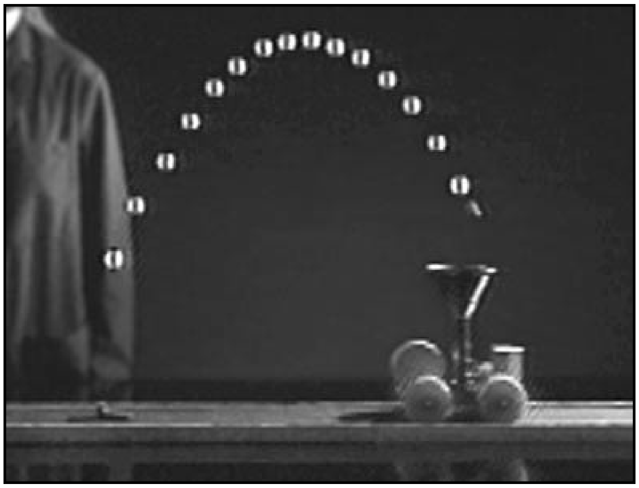

Figure 1

[†] Sutton, *Demonstration Experiments in Physics*, Demonstration M-99, Relativity Car, page 46.
Richard M. Sutton, Three Demonstration Experiments on Projectile Motion, *Am. J. Phys.* 12, 104-105 (1944).
Meiners, *Physics Demonstration Experiments,* Section 7-2.16, page 127.

In this demonstration a small car will roll down a track at constant speed. When the car reaches this point, it will fire a ball straight up as it continues to move. After the ball is fired, will it come down ahead of, on top of, or behind the car?

It comes down onto the car. This shot in stop motion shows that the ball stays directly above the car at all times.

What will the shape of the ball's path be through the air?

The ball flies in a parabola. The combination of constant horizontal velocity and constant vertical acceleration produces a parabolic path.

Equipment

1. Cannon car (complete with cocking mechanism, trigger release, and catcher-barrel with funnel).
2. Horizontal track or guided roadway (complete with trigger trip to fire projectile).
3. Projectile (steel ball).
4. Cocking stick (wooden ramrod).
5. Stopping device to protect cannon car from any unwanted collisions.

Demo 02-04 Vertical Gun on Accelerated Car

This demonstration presents two experiments dealing with different aspects of the effect of acceleration on the vertical gun and car experiment shown in Demonstration 02-03.

In the first part of the demonstration the experiment is done with the track inclined, so that the car accelerates down the incline. The ball is ejected perpendicular to the track, as before. It is easy to see that the car accelerates down the incline. It is not as easy to recognize that because the track is inclined the ball has that same component of acceleration along the incline as the car, so the ball will again fall into the funnel, as illustrated in *Figure 1*.[†]

In the second experiment, the car is accelerated along the horizontal track by connecting it to a weight by a string passing over a pulley. In this case the car continues to accelerate after the ball is ejected, so the ball lands behind the funnel, as illustrated in *Figure 2*.

Figure 1

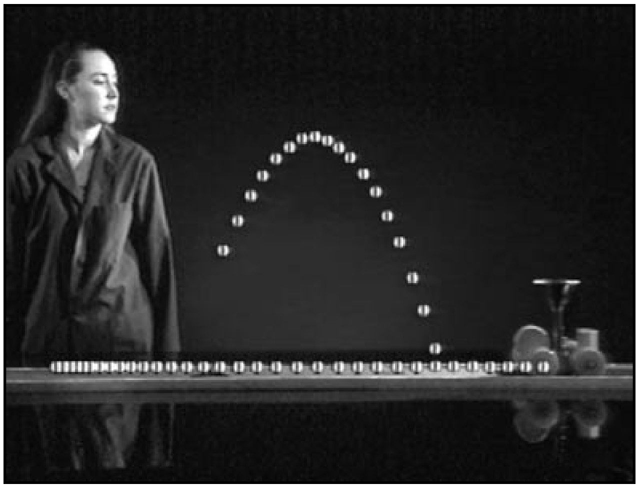

Figure 2

[†] Fred B. Otto, Modified Ballistic Car Demonstration, *Am. J. Phys.* 42, 326 (1974).
Albert A. Bartlett, Modified Ballistic Car Demonstration, *Am. J. Phys.* 43, 732-733 (1975).
Robert Prigo and Abel Rosales, More general and interesting versions of the Ballistics Cart and Tunnel Demonstration, *Am. J. Phys.* 44, 783-785 (1976).

Vertical Gun on Accelerated Car / Script

A small car with a ball-firing mechanism on the top runs down a tilted track so that it is constantly accelerating. When it reaches this point it will fire the ball straight out of the cannon and continue on.

After the ball is fired, will it land ahead of, on top of, or behind the car?

It lands on top of the car. Here is a stop-motion look at the sequence showing the position of the ball with respect to the car after it is fired.

This time the car will be pulled along the track by a weight hanging over a pulley, and will also be accelerating constantly.

Where will the ball land this time?

The ball lands behind the car.

Equipment

1. Inclined track. Same as Demonstration 02-03, but with back end of track elevated.
2. Horizontal track. Same as Demonstration 02-03, but the car is pulled by a string and weight over a pulley.

Demo 02-05 Air Table Parabolas

Pucks are projected at an uphill angle along a tilted air table. The motion of the puck then is described by a constant velocity in the direction perpendicular to the tilt and a constant acceleration in the direction of the tilt. As in the case of a standard projectile, this leads to motion of the pucks along parabolic paths.[†]

The video shows three projectile paths, with the air table tilted at 3°, 6°, and 9°, respectively. The position of the puck at a series of equal time intervals is marked on the screen so that the shape of the parabolas can be studied and the vertical acceleration and the horizontal velocity can be experimentally obtained. The parabola for the case of 6° is shown in *Figure 1*.

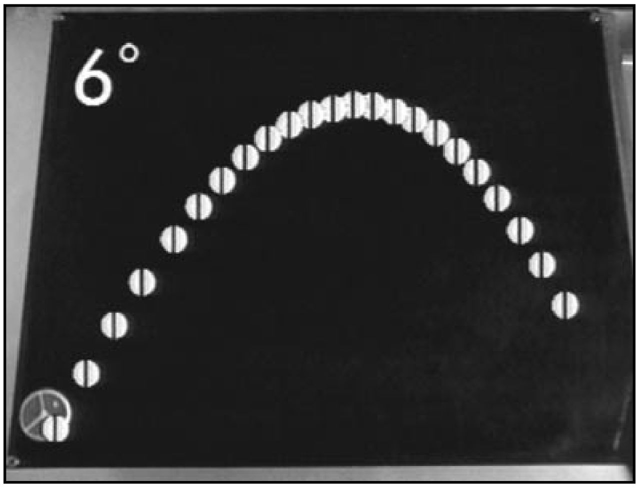

Figure 1

[†] Sutton, *Demonstration Experiments in Physics*, Demonstration M-96, Parabolic Path of Projectile, page 45.
Freier and Anderson, *A Demonstration Handbook for Physics*, Demonstration Mb-20, Blackboard Trajectory.

If the value of gravitational acceleration on the Earth could be changed, how would it affect the motion of falling bodies?

We can simulate such a change with this air table. If we tilt the table, we get a component of gravitational force along this axis of the table, and the puck will accelerate in that direction. Here are three launches with the table tilted to different angles.

3 degrees

6 degrees

9 degrees

Here are all three launches repeated with dots tracking the position of the puck every one-tenth second.

Equipment

1. Clean air table.
2. Air supply system.
3. Pucks with clean flat bottoms.

Demo 02-06 Range Gun

Projectiles are released with the same muzzle velocity at a number of angles with respect to a horizontal surface.

Interesting investigations involve how the range of the projectile varies with the angle of projection and at what angle the range of the projectile is a maximum. These problems are experimentally investigated using the "Range Gun."†

Two results can be observed:
(1) The range of the projectile is a maximum when the angle of projection is 45° above the horizontal.
(2) The range of the projectile is the same for angles differing from 45° by the same amount. For example, the ranges of 60° and 30° projectiles are the same (45° + 10°), as are the ranges of 75° and 15° projectiles.

Figure 1 shows the trajectories taken by projectiles with the same muzzle velocity projected at various angles above the horizontal.

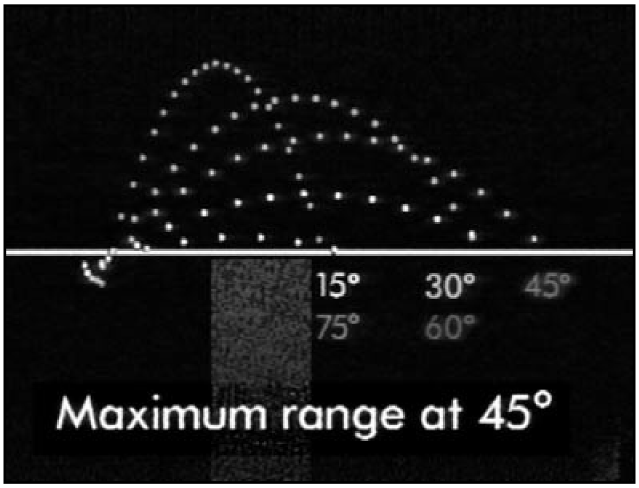

Figure 1

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† Sutton, *Demonstration Experiments in Physics*, Demonstration M-95, Range of a Projectile.
Freier and Anderson, *A Demonstration Handbook for Physics*, Demonstration Mb-20, Blackboard Trajectory; Demonstration Mb-19, Water Trajectory.
H. A. Buckmaster, Ideal ballistic trajectories revisited, *Am. J. Phys.* 53, 638-641 (1985), and references therein.

At what angle should a ball be launched in order to fly the greatest distance before striking the ground?

This spring-loaded gun can launch small wooden balls at different angles with the same speed.

As we shoot each ball we will track its position with a line on the screen, using a different color for each angle of firing.

Equipment

1. Spring gun with cocking mechanism and trigger. The angle of firing is fully adjustable between 0° and 90°.
2. Gun is mounted in such a way that it can be clamped to a table top, which in turn serves as the impact plane.
3. Markers for the point of impact for each angle fired are helpful.

Demo 02-07 Vector Velocity Addition

This demonstration uses a Ping-Pong ball that is confined in a rolling clear glass tube to illustrate addition of components of displacement.

We can move the tube with the ball at rest inside it from right to left, causing a horizontal displacement of the ball. If we connect the ball by a taut string to a point at the top end of the tube, moving the tube results in a vertical displacement of the ball equal to its horizontal displacement. The ball then moves with the vector sum of these displacements, at an angle of 45° to either of the individual component displacements, as shown in *Figure 1*.[†]

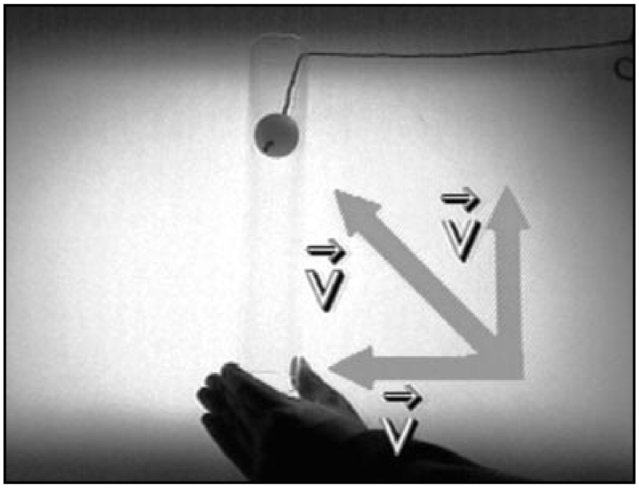

Figure 1

[†] Sutton, *Demonstration Experiments in Physics*, Demonstration M-73, Vector Addition of Displacements; and M-74.

Vector Velocity Addition / Script

We'll use this Ping-Pong ball on a string and a glass tube to demonstrate the vector addition of two velocities.

The ball is first pulled straight up the tube, giving it a velocity in the vertical direction.

Now the tube is moved to the left with the ball at the bottom, giving the ball a velocity to the left.

When the top of the string is held stationary while the tube is moved to the left, the ball moves up the tube and to the side at the same time. The vertical and horizontal velocities of the ball have equal magnitudes, and their sum is a velocity at 45 degrees to both.

Equipment

1. Background to serve as the coordinate plane.
2. Ping-Pong ball attached to a string.
3. A glass tube approximately 50 cm long whose I.D. is a little larger than the ball's diameter.

Demo 02-08 Bulldozer on Moving Sheet (2D)

A toy bulldozer moving under its own power on a moving plastic sheet is used to illustrate a variety of vector velocity examples.[†]

In the first example, the bulldozer moves across the plastic sheet, which is moving with half the speed of the bulldozer, leading to a bulldozer velocity at about 27° in the laboratory frame of reference with respect to the component velocities, as illustrated in *Figure 1*.

In the second example, the plastic cloth is pulled at the same speed that the bulldozer moves, leading to a bulldozer velocity at 45° between the two component velocities, as illustrated in *Figure 2* .

In the third example, the bulldozer is aimed at about 45° backward from the direction the plastic sheet is moving, and the plastic sheet is pulled at about 0.7 times the velocity of the bulldozer. The bulldozer then appears to move directly across the plastic sheet, as illustrated in *Figure 3*.

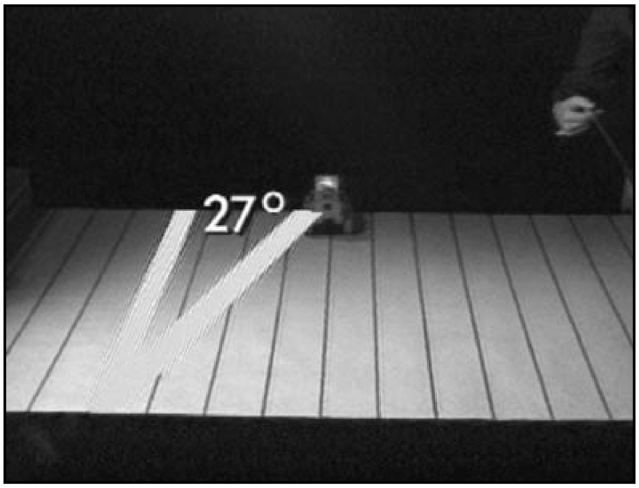

Figure 1

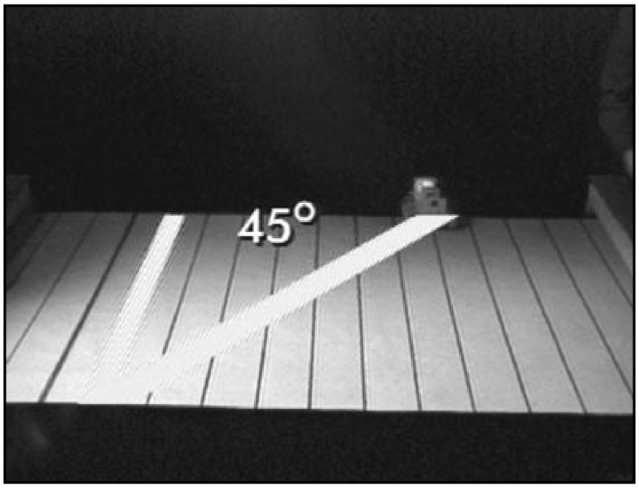

Figure 2

[†] Sutton, *Demonstration Experiments in Physics*, Demonstration M-75, Vector Addition of Velocities.

Bulldozer on Moving Sheet (2D) *Demo 02-08*

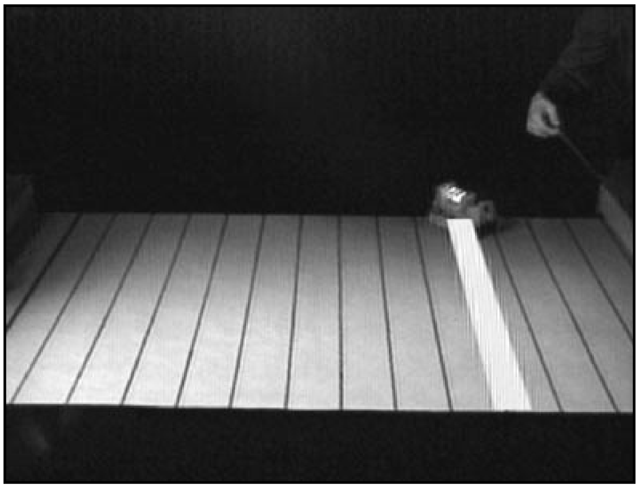

Figure 3

Bulldozer on Moving Sheet (2D) / Script *Demo 02-08*

This toy bulldozer, which runs at a constant speed, will be used to show how velocities add together in two dimensions.

The bulldozer is set on a paper sheet that can be pulled along the table at a constant velocity. The bulldozer is first set up to run directly across the sheet, and it follows this path.

This time the sheet will be pulled to the right at half the speed of the bulldozer. What will the path of the bulldozer be?

The bulldozer moves at approximately 27 degrees to its previous path. What will the path be if the sheet is pulled at the same speed as the bulldozer?

The bulldozer moves across at 45 degrees to its original path.

If we now aim the bulldozer at 45 degrees to the left, how fast must the sheet be pulled to the right if we want the bulldozer to move straight across?

Pulling the sheet to the right at approximately seven-tenths of the bulldozer's speed makes the bulldozer move straight across.

Equipment

1. Battery driven bulldozer or similar device.
2. Long sheet of heavy paper or plastic sheet to serve as the analog for a "river." (Can be pulled by hand or some substitute mechanism).

Demo 02-09 Sliding Weights with Triangle

In this experiment beads are allowed to slide along the sides of a wire triangle oriented in a vertical plane, as shown in *Figure 1*. The lengths and sides of the triangle are chosen so that the bead requires the same time to slide from the upper to the lower point along any of the three sides under the influence of gravity.

The vertical side is of length L, so from the equation for distance as a function of time for a constant acceleration g, the time required will be

$$t = \sqrt{\frac{2L}{g}}$$

If the side is oriented at some angle θ with respect to the vertical, and if its length is $L \sin\theta$, then the time required will be the same, because the acceleration

$$a = g \sin\theta$$

so the length of the side and the acceleration of the bead change in the same proportion:

$$t = \sqrt{\frac{2L\sin\theta}{g\sin\theta}} = \sqrt{\frac{2L}{g}}$$

The times required for the bead to travel along the sides are compared, two at a time, and shown in real time and in slow motion.

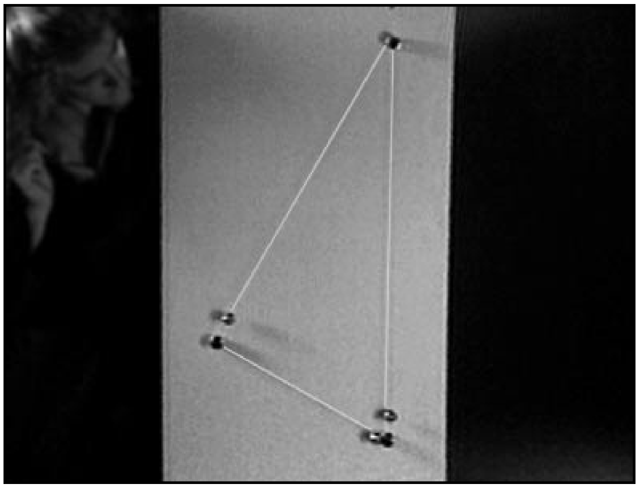

Figure 1

Sliding Weights with Triangle / Script

The freely sliding weights on this wire triangle can be used to demonstrate different accelerations due to the force of gravity.

This wire points straight down, and is 60 centimeters long. This wire is at 30 degrees to vertical and is 52 centimeters long. If their weights are released together, which will reach the end first?

The weights reach the bottom at the same time.

This wire is at 60 degrees to the vertical and is 30 centimeters long. If these two balls are released together, they also hit at the same time.

Equipment

1. A substrate (ideally with a base) strong enough to hold very taut wires in the triangular shape discussed above. (Stainless steel is preferable to minimize rusting and its associated friction).
2. Three brass ball bearings drilled slightly oversized through their centers to permit “stringing” with the wire.

Demo 02-10 Sailing Upwind

This demonstration shows experimentally how a boat can sail with a component of velocity against the wind.

Figure 1 presents the geometry of this situation and shows the relationship between the direction of the wind, the orientation of the sail, and the resulting velocity of the boat with its orientation. Also shown are the force of the wind on the sail, and the velocity of the boat and its component in the direction from which the wind is blowing. The boat does have a component of velocity in the direction the wind is blowing from, hence the description "sailing against the wind."

This problem has been discussed thoroughly in the literature, both theoretically and experimentally.†

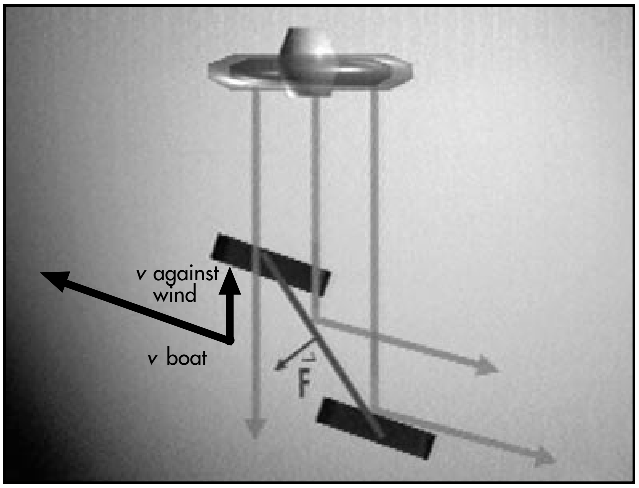

Figure 1

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† Paul G. Hewitt, Sailboat Demonstration, *Phys. Teach.* 6, 79-80 (1968).
R. E. Benenson, Andrew Hmiel, and Kathleen Kowsky, Air Track to Demonstrate Sailing into the Wind, *Phys. Teach.* 16, 505-506 (1978).
George C. Goldenbaum, Equilibrium Sailing Velocities, *Am. J. Phys.* 56, 209-215 (1988), and references therein.
Halsey C. Herreshoff and J. N. Newman, The Study of Sailing Yachts, *Scientific American* Vol. 215 #2, August 1966, pp.60-68.

Sailing Upwind / Script

Sailboats do not have to sail in the direction of the wind. With the sails properly set, a sailboat can actually sail into the wind. We'll use these roller skates with a sail to show how it's done.

The wheels of the skates can not turn, and can therefore roll in only one direction. That's like the keel on a sailboat, which largely prevents the boat from moving sideways.

This fan will blow air from the front and side, with the sail tilted to a sharp angle. The skate rolls toward the wind.

This animation shows the force resulting from the wind blowing on the sail.

Since the skates cannot move in this direction, they roll toward the wind.

Equipment

1. A large source of wind (a large fan with several streamers works well).
2. An analog for a sailboat (ours was built from roller skates using foamcore as the sail).

Demo 02-11 Local Vertical with Acceleration

This demonstration uses a standard liquid accelerometer, mounted on an air track glider, to show that there is no net force component down an incline along which an object is freely accelerating, in the frame of reference of the moving object.†

As an air track glider accelerates along an inclined air track, liquid in an accelerometer mounted on the glider is in equilibrium with its surface parallel to the incline of the air track. In the frame of reference of the glider, the dynamical situation resembles that in a freely falling frame of reference, for the direction along which the acceleration is occurring. Thus, objects in the accelerating frame will not experience any weight component along the direction they are accelerating, and the liquid surface will be in equilibrium parallel to the angle of incline, as illustrated in *Figure 1*.

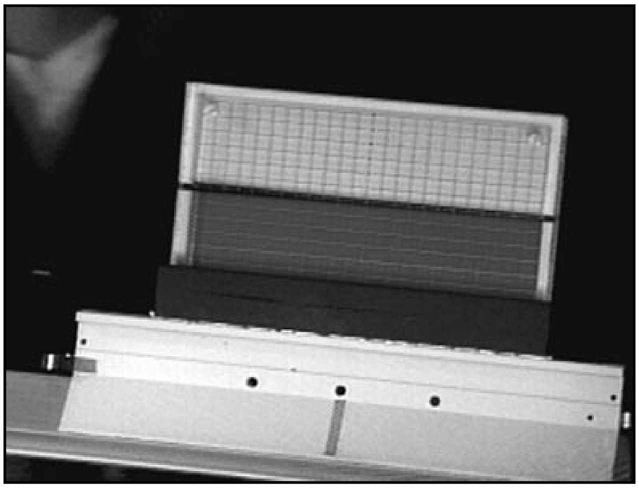

Figure 1

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† Sutton, *Demonstration Experiments in Physics*, Demonstration M-289, Liquid Accelerometer. *Project Physics Resource Book*, (Holt, Rinehart, and Winston, New York, 1975), page 47. J. Harris and A. Ahlgren, Some Simple Experiments and Demonstrations, *Phys. Teach.* 4, 314-322 (1966).

If a small container filled with water is tilted, the water surface remains level and horizontal.

If we place the container on a glider and set it on a tilted track, the water surface is horizontal even though the track is tilted.

If we force a cushion of air beneath the glider so that the glider accelerates freely down the track, what will happen to the surface of the water?

The water surface becomes parallel with the track, as if the force leveling the surface pulls perpendicular to the track.

Equipment

1. Tilted long air track.
2. Blower system.
3. Large glider with liquid accelerometer (with its level line clearly marked).

CHAPTER 5

INERTIA

Demo 02-12 Shifted Air Track Inertia

This demonstration illustrates Newton's first law, by showing that if an object experiences no force, it will not move.

A glider is placed on an air track that has no air flowing. When the air track is moved back and forth, the glider sticks to the air track because of friction, and moves back and forth with the air track.

When the air is turned on, the glider floats virtually without friction on a thin layer of air, and remains fixed in space as the air track moves back and forth under it.

The perceptive observer will notice that the glider is moving very slightly. This is caused by a small amount of residual friction.

Figure 1

Shifted Air Track Inertia / Script

If a glider is at rest on a track, and the track is shifted from side to side, the glider will move with the track. Air is now forced through holes in the side of the track so that the glider is supported on a cushion of air.

What will happen now if we shift the track from side to side with the air turned on?

The glider is now motionless. If we give the stationary glider a single push, it moves at a constant speed after the force is gone.

Equipment

1. Short air track.
2. Blower system.
3. Heavy cart capable of supporting entire load.
4. Largest glider with extra masses to maximize the inertia of the glider assembly.

Demo 02-13 Inertia Ball

A heavy cylinder hangs by a thin rope from a rigid frame. A second identical thin rope is attached to the bottom of the cylinder, and a short metal rod is attached to the bottom end of the lower rope, as shown in *Figure 1*. When a force is exerted downward on the rod, which rope will break?

Two experiments are shown in the video.[†] In the first, the rope is pulled slowly. In this case, the weight of the cylinder adds to the downward force exerted on the rod, and the top rope breaks. In the second, the rod is pulled with a rapid jerk. This causes the lower string to break, due to the greater tension in the lower string caused by the inertia of the heavy metal cylinder. The inertia of the block doesn't by itself cause the large tension in the lower string, but it makes the tension in the upper string less than that in the lower string. For the upper string to have high tension, the weight must move down and stretch the upper string. That happens slowly enough so that the lower string breaks first.

The black horizontal beam in the support frame catches the heavy cylinder, preventing serious injury to the experimenter's hands.

This demonstration has been discussed often in the literature of physics.[‡]

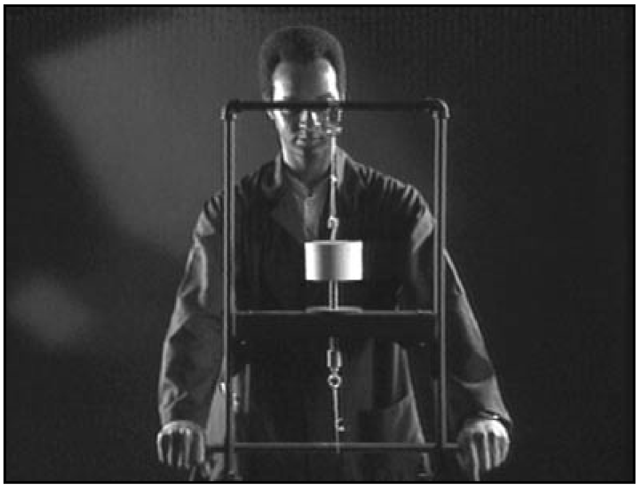

Figure 1

[†] Sutton, *Demonstration Experiments in Physics*, Demonstration M-100, Inertial Reaction, pp. 46-47; Demonstration M-101, Breaking a Rope by Inertia.
Freier and Anderson, *A Demonstration Handbook for Physics*, Demonstration Mc-2, Inertia Balls.

[‡] P. Le Corbeiller, A Classical Experiment Illustrating the Notion of "Jerk," *Am. J. Phys.* 13, 156-158 (1945).
Frank G. Karioris, Inertia demonstration revisited, *Am. J. Phys.* 46, 710-713 (1978).

This heavy weight hangs from a light string, with another string looped around its lower hook. If a metal bar is held at the bottom of the lower loop and the bar is pushed down, the upper string breaks.

We'll repeat that with a new string; again, the upper string breaks.

Is there any way to get the lower string to break?

If we yank down quickly on the bar, the lower string breaks.

Equipment

1. Framework and base assembly strong enough to bear the additive forces (and abuse) while at the same time minimizing unwanted vibrations.
2. A massive object (containing lead perhaps) with hooks above and below.
3. A supply of string loops (just strong enough to safely support their load) that are identical in strength, length, and knots (bowline knots are recommended).
4. 50-cm bar.

Demo 02-14 Foam Rock

This demonstration shows the effect of inertia.

A standard heavy rock is hit squarely with a large rubber hammer, resulting in negligible motion of the rock due to its large inertia.

On the other hand, when an imitation rock made from light foam is struck with the hammer in the same way, it rapidly moves away because of its very small inertia.

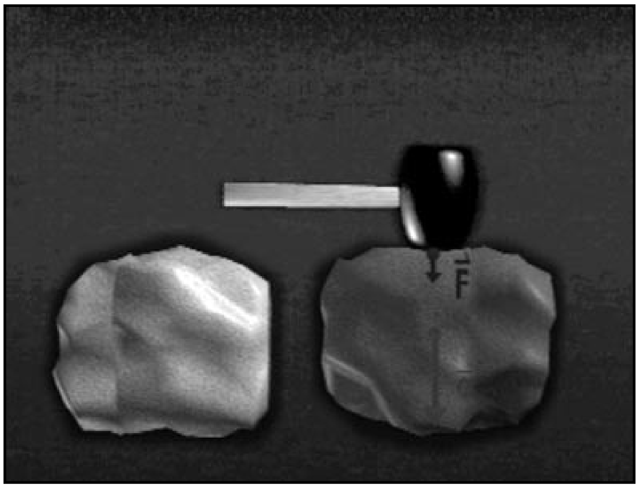

Figure 1

Foam Rock / Script

When this large rock is struck with a hammer, it barely moves.

Why does this rock behave differently?

The first rock is real, and very massive. The force of the blow barely accelerates it at all. The second rock is made of low-mass foam rubber. The same blow from the hammer on this rock causes a very high acceleration.

Equipment

1. Large rock.
2. Fake rock of similar size and appearance. (Ours was fabricated by bonding several sheets of foam together. The foam was then cut and torn to closely resemble the real rock, then painted appropriately).
3. Large rubber hammer.

Demo 02-15 Tablecloth Jerk

This demonstration shows the old magician's trick of pulling a silk tablecloth out from under a dining room setting without upsetting any of the items on the tablecloth. Of course it is not magic, but physics.†

The explanation of this and other similar phenomena is generally said naively to be "inertia." The inertia of the items in the table setting keeps them in place while the slippery silk tablecloth is rapidly pulled out from under them. Interesting articles discuss other aspects of physics that bear upon this phenomenon.‡

Figure 1

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† Sutton, *Demonstration Experiments in Physics*, Demonstration M-104, Inertia Tricks, pp. 47-48. Freier and Anderson, *A Demonstration Handbook for Physics*, Demonstration Mc-4, Inertia of Rest.

‡ H. T. Hudson, There's More to It than Inertia, *Phys.Teach*. 23, 163, (1985). Uri Haber-Schaim and John H. Dodge, There's More to It than Friction, *Phys. Teach*. 29, 56-57 (1991).

Tablecloth Jerk / Script

We'll try to remove the tablecloth from under these dishes without making a mess. How? By yanking the cloth out very fast.

Pull slowly, and the table setting moves. This will have to be done much more quickly.

A metal tube wrapped inside the loose edge of the cloth provides a firm grip for a fast pull. When the cloth is yanked out fast, the dishes barely move.

Equipment

1. Tablecloth. (Use anything from silk to broadcloth with high-gloss, low friction surface—no hems! Heavy brown paper can also be used).
2. Tableware (choose massive items with low friction surfaces).
3. A smooth tabletop, of course, is very helpful.

Demo 02-16 Eggs and Pizza Pan

This demonstration illustrates much the same concepts in physics as the previous tablecloth trick demonstration.†

Three raw eggs are positioned directly above three glasses of water on three cardboard tubes that rest on a pizza pan which in turn sits on the water glasses. The situation is shown in *Figure 1*. The handle of a broom is used to rapidly knock the pizza pan and the cardboard tubes out from under the eggs, whereupon they fall into the glasses of water. The action is repeated in slow motion.

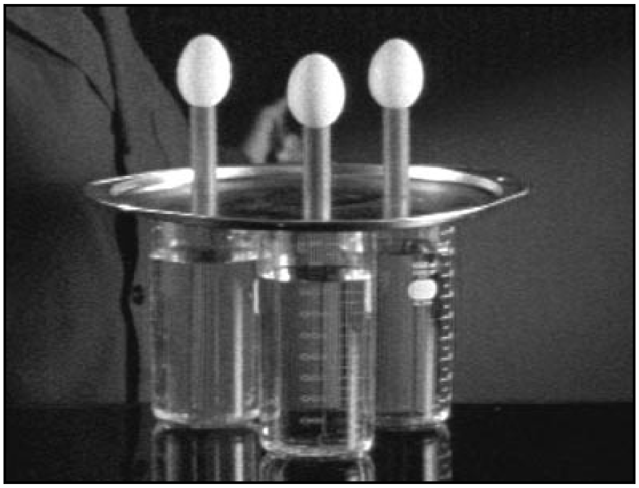

Figure 1

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† Meiners, *Physics Demonstration Experiments*, Section 8-2.2, p.141.

Eggs and Pizza Pan / Script

Could you remove this pizza pan from under these eggs without touching or breaking the eggs? If the eggs could be made to drop straight down, they would land in these water-filled beakers and would survive intact.

By striking the pizza pan hard with this broom handle the pan will fly out, allowing the eggs to drop straight down into the beakers. Let's try it.

The pizza pan shot out so fast that the eggs barely moved. Let's watch again in slow motion.

Equipment

1. One or more small containers of water.
2. Pizza pan or small tray with a low profile lip.
3. Cylinders (PVC tubing, rolled 3x5 cards, etc., with sufficient diameter to support eggs but still not allow them to "cradle" the eggs too deeply).
4. Appropriate number of raw eggs.
5. Stiff household-type straw broom.
6. Solid table with "leading edge" top design.

Demo 02-17 Pencil and Plywood

In a tornado or other atmospheric disturbance with high wind velocities, at times thin lightweight objects can move so rapidly that they become impaled on apparently stronger objects. For example, a piece of hay or straw may be driven into a tree trunk, or a wooden 2x4 may become impaled on a concrete wall.

This demonstration uses the inertia of a rapidly moving pencil to impale it on a piece of ½ inch plywood. The action is also repeated in slow motion.

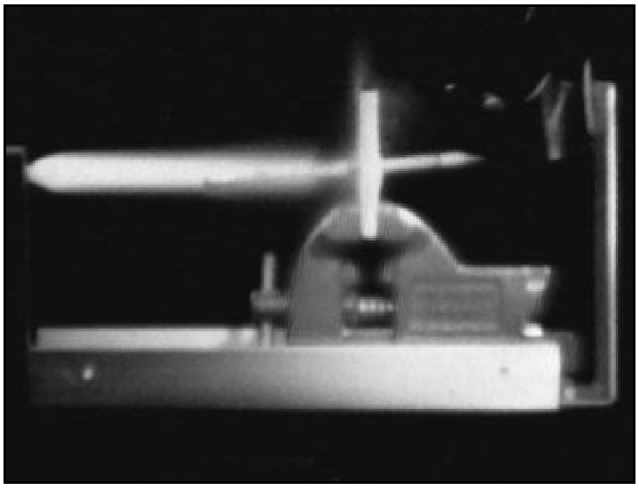

Figure 1

Pencil and Plywood / Script

We will blast a pencil through a piece of plywood using a carbon-dioxide fire extinguisher.

A pencil is inserted into this tube and a carbon dioxide fire extinguisher is connected to the end of the tube. When the fire extinguisher is activated, it will drive the pencil through the tube into a piece of plywood positioned at the exit of the tube.

Here is the action repeated in slow motion.

Equipment

1. Securely mounted barrel whose inside diameter is only slightly larger than the outside diameter of a typical pencil and affixed with a quick-disconnect fastener of appropriate size.
2. Firmly mounted vice to hold the plywood target.
3. Safety backstop.
4. CO_2 fire extinguisher whose horn and any additional deflection apparatus (designed to create the fogging) has been removed and replaced with the remaining half of the quick-disconnect.

CHAPTER 6

ACTION AND REACTION

Demo 02-18 Reaction Gliders

Two identical air track gliders are used to illustrate Newton's third law of motion: "For every action there is an equal and opposite reaction."

The two gliders are initially at rest, tied together with a compressed spring between them, as illustrated in *Figure 1*.[†] When the string tying the two gliders together is burned, the gliders immediately move in opposite directions with equal speeds.

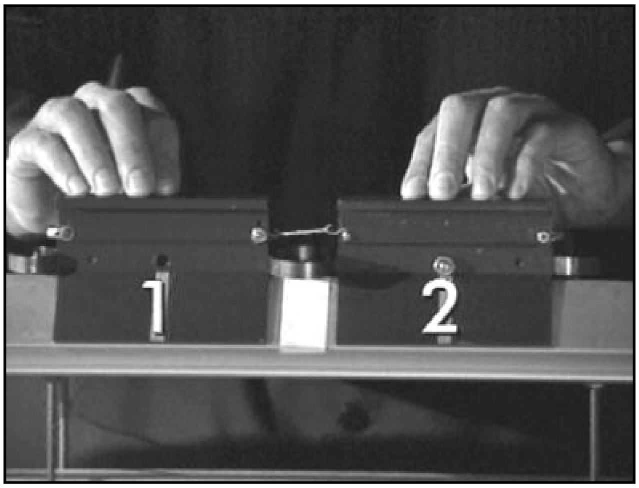

Figure 1

[†] Freier and Anderson, *A Demonstration Handbook for Physics*, Demonstration Md-1, Reaction Carts; Demonstration Md-4, Action and Reaction with Air Carts.

If one object pushes on a second object, the second object accelerates. But what about the object doing the pushing? Does it also accelerate? We will use these gliders floating on an air track to find out.

This spring bumper will provide the force from the first cart on the second.

If we tie the carts together with a string so that the first cart is pushing on the second, then burn the string, what will happen to the first cart?

Both carts accelerate. When one object pushes another, the second object pushes back. For every action, there is an equal and opposite reaction.

Equipment

1. Short level air track.
2. Blower system.
3. Two gliders of equal mass and identical spring steel bumpers. The gliders have been equipped with hooks for the string loop. One glider is equipped to hold additional weights to double its mass.
4. Air shield to place on the air track between the carts to permit easy burning of the string loop.
5. Source of flame.
6. Supply of string loops—a bowline or other non-slip knot is recommended.

Demo 02-19 Reaction Gliders Momentum Conservation

This demonstration expands Demonstration 02-18 to the case of unequal gliders.

Two gliders with masses in the ratio of 2:1 initially at rest are tied together by a string with a compressed spring between them. The string is then burned, and the gliders move away from each other. By reference to Newton's third law, the impulse given to each of the gliders by the spring during their separation must be equal and opposite. Thus, their momenta must be equal in magnitude but opposite in direction and their speeds must be in the ratio of 2:1, with the smaller glider having the larger speed.

Alternatively, we can view this problem in terms of the center of mass. Because the two gliders were at rest before the string is burned, their center of mass must remain at rest after they begin to move, so the more massive glider moves away with half the velocity of the smaller glider. Equal mass gliders move away with equal speeds.

This can be verified mathematically by taking velocity data from the video.

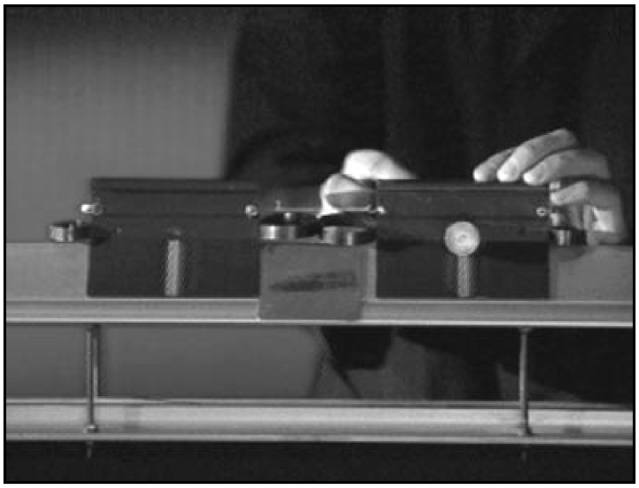

Figure 1

These two equal mass gliders with spring bumpers are moving on a nearly frictionless air track.

If we tie the gliders together with a string, the springs try to push the gliders apart. If the string is burned, the gliders fly apart with equal but opposite velocities.

If we now double the mass of one of the gliders and repeat the demonstration, what will the relative velocities of the gliders be after the string is burned?

The glider with twice the mass now moves away at half the velocity of the lighter glider.

Equipment

See Demonstration 02-18.

Demo 02-20 Car on Rolling Board

This demonstration illustrates the concept of action and reaction.

A radio-controlled car moves along a board that lies on a series of rollers to reduce friction between the board and the table.† When the car accelerates in one direction, the board accelerates in the opposite direction, due to the action-reaction force pair between the tires and the board. The car wheels apply a force on the board, causing it to move. The board applies a reaction force on the car wheels, causing the car to move along the board. This situation is illustrated with graphics in *Figure 1*.

Ideally, the momentum of the car and the board would remain equal and opposite at all times. However, frictional losses limit this symmetry in the actual experiment.

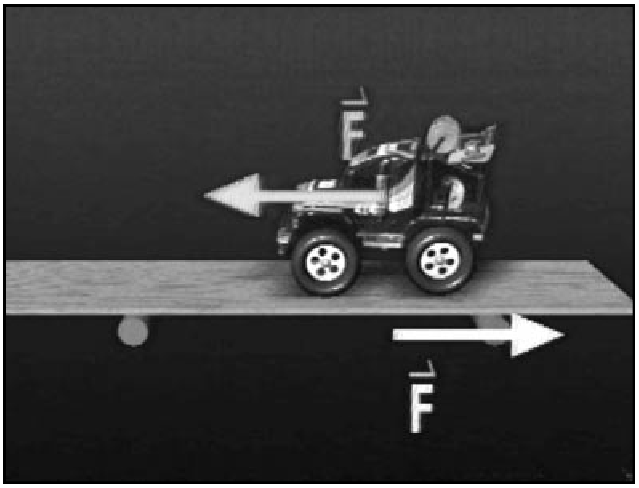

Figure 1

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† Sutton, *Demonstration Experiments in Physics*, Demonstration M-123, Reaction Track, p. 55.

Car on Rolling Board / Script

We'll use this radio-controlled car and a board on rollers to demonstrate action and reaction forces.

The car and board are both initially at rest. When we start the car moving to the left, the board moves to the right.

The car exerts a force on the board, and the board exerts an equal and opposite force on the car.

This animation shows the forces that act between the car and the board.

Equipment

1. Remote-controlled, battery-powered car.
2. Light board to serve as freely floating roadway.
3. Several rollers to support roadway above table.

Demo 02-21 Fan Car with Sail

The "fan car" was developed as part of the Harvard Project Physics program to illustrate Newton's third law: "For every action there is an equal and opposite reaction."†

When a fan mounted on the car blows air, the car reacts by moving in the opposite direction. When a sail attached to the car is positioned in front of the fan so as to catch all of the wind from the fan, the car does not move. The air hitting the sail is redirected, spreading out perpendicular to its original direction, so the force exerted by the air on the sail and the reaction force of the air on the propeller are equal in magnitude but opposite in direction, as illustrated in the video graphics and in *Figure 1*.

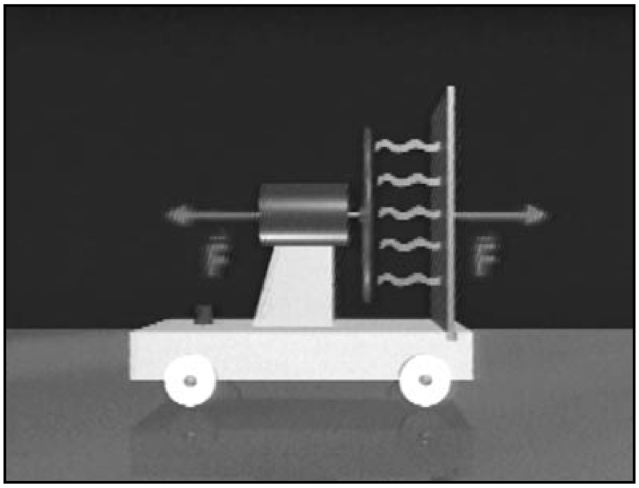

Figure 1

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† *Project Physics Resource Book* (Holt, Rinehart, and Winston, New York, 1975) D19 Newton's Third Law, page 43.
J. Harris and A. Ahlgren, Harvard Project Physics, Some Simple Experiments and Demonstrations, *Phys. Teach.* 4, 314-322 (1966).
Steven R. Smith and Jerry D. Wilson, A New Design to Demonstrate Newton's Third Law, *Phys. Teach.* 10, 208-209 (1972).
Meiners, *Physics Demonstration Experiments,* Section 7-1.5, p. 103.

Fan Car with Sail / Script

This small cart has a motorized fan mounted on top. When we turn on the fan, the cart moves off to the side. If we put a sail on the cart and turn on the fan, which direction will the cart move?

The cart doesn't move at all. If we blow on the cart with a fan which is not attached to the cart, the cart moves in the direction of the airflow.

This animation shows the force acting on the cart without the sail.

Here are the forces acting on the cart when the sail is in place.

And this is the force which acts on the cart when the external fan is used.

Equipment

1. Small cart equipped with motor driven fan that is battery-powered.
2. Sail that can be conveniently attached to the cart.
3. Sizable fan to serve as an external source of wind (paper streamers increase visibility).

Demo 02-22 CO_2 Rocket

A small canister of compressed CO_2 is used to accelerate a type of Hero's engine, illustrating the idea of action and reaction.[†]

A standard compressed carbon dioxide cartridge, commercially available for use with racing cars and rockets, exhausts its gas along the tangent of a circle as its holder spins in the opposite direction. This is similar to the case of a water sprinkler. The pressure of the gas in the cartridge pushes the gas out. The reaction force that the exhausted gas exerts on the cartridge causes the system to rotate in the direction opposite to that of the exhausting gas.

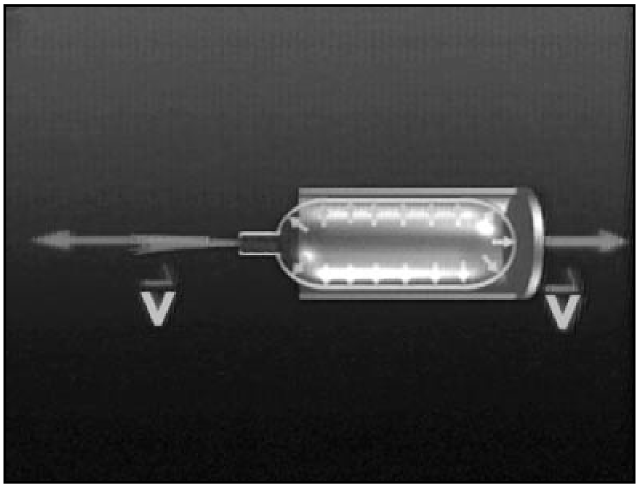

Figure 1

[†] Freier and Anderson, *A Demonstration Handbook for Physics*, Demonstration Mh-1, Rocket Car; Demonstration Mh-2, Rocket to the Moon.

CO_2 Rocket / Script

We'll make this rotation stand spin using the force provided by a small cylinder filled with carbon dioxide.

When the back of the cylinder is punctured with a pin, the carbon dioxide jets out of the cylinder, and the stand rotates in the opposite direction as the escaping gas.

This animation shows the pressure acting on the inside of the carbon dioxide cylinder before and after it is punctured.

Equipment

1. Rotating bar securely mounted to a heavy base via a good bearing system. The bar has a containment cup on one end and a counterbalance on the other end.
2. Firing mechanism to puncture the CO_2 cartridge.
3. Supply of CO_2 cartridges.
4. Clamps to attach the rotator base to the table.

Demo 02-23 Water Rocket

A commercially available water rocket is used to illustrate the idea of action and reaction applied to rocketry.

Air is pumped into the body of the rocket under pressure. When the air is released, the pressure within the rocket forces the air out as exhaust. The reaction force of the exhaust air on the rocket gives the rocket its thrust. When a small amount of water is exhausted with the pressurized air, the rocket experiences a much greater thrust, due to the greater momentum of the water in the exhaust.[†] Clearly, neither the pressure alone nor the energy stored in the rocket alone is responsible for this phenomenon.

Figure 1

[†] Freier and Anderson, *A Demonstration Handbook for Physics*, Demonstration Mh-2, Water Rocket.

Water Rocket / Script

Here is a toy water rocket. We're going to fire the rocket first with water exhaust then with air only, and show the difference in the rocket's acceleration.

We'll first fill the rocket half full of water, then pump the handle 10 times to raise the pressure in the rocket.

When the rocket is launched, the water exhaust boosts it very high.

If we leave the water out, and fill the rocket with air only, how high will it go?

We'll pump the rocket twice as many times to make the pressure in the rocket the same as the last time.

Here goes.

The rocket hardly moves at all.

Equipment

1. Toy water rocket.
2. Funnel—supplied with rocket.
3. Air pump—supplied with rocket.
4. Supply of water.

Demo 02-24 Fire Extinguisher Wagon

A carbon dioxide fire extinguisher serves as the engine for a wagon rocket, illustrating Newton's third law.

The carbon dioxide exhaust is directed out of the back of the wagon, so the wagon is propelled forward like a rocket.†

Figure 1

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† Evan Jones and P. Peter Urone, Spectacular Rocket Experiment, *Phys. Teach*. 14. 112-113 (1976).

The spray from a carbon dioxide fire extinguisher looks a lot like the exhaust of a rocket. And like a real rocket exhaust, the escaping CO_2 can accelerate a large mass. We'll use this extinguisher mounted on a rolling wagon to accelerate a person to suborbital speed.

3… 2… 1… Blastoff!

Engine cutoff.

Equipment

1. Wagon or large cart.
2. Device to safely cradle the fire extinguisher.
3. CO_2 fire extinguisher with the deflection and flogging apparatus removed.
4. Attach the free end of the hose to the wagon with a half-inch union plumbing fitting so the exhaust exits straight out the back end opposite the desired direction of travel.
5. Goggles, etc., if desired.

Demo 02-25 Helicopter Rotor

A toy propeller is held vertically and given a rapid spin. The spinning of the propeller deflects air downward, causing an upward lift force on the propeller, and it rises, as illustrated in *Figure 1*. This demonstration is a further illustration of Newton's third law.

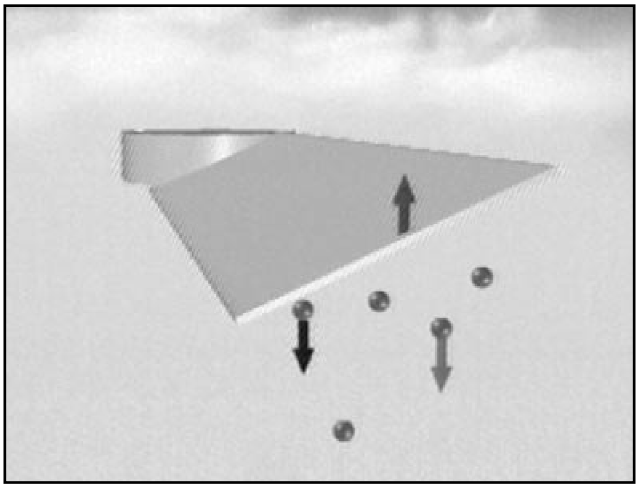

Figure 1

Helicopter Rotor / Script

This rotor has tilted blades like those on a helicopter.

When we spin the rotor by pulling on a string, the rotor flies straight up.

This animation shows how the rotor pushes air molecules down as it spins. The reaction forces from the air molecules push the rotor up.

Equipment

Toy propeller.

Demo 02-26 See-Saw Reaction Carts

This demonstration illustrates action and reaction forces using a center of mass balance board.

Two carts are held together by a spring while sitting in the middle of a long board balanced on a fulcrum, as illustrated in *Figure 1*. When the spring is released, the carts separate and roll away from each other along the two sides of the balanced board.†

The system was in balance initially with the center of mass directly above the fulcrum. As the carts separate, the center of mass does not move, so the board remains in balance. This is a direct verification of the center of mass idea mentioned in Demonstration 02-19.

Figure 1

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† Freier and Anderson, *A Demonstration Handbook for Physics*, Demonstration Mp-16, See-Saw Center of Mass.

See-Saw Reaction Carts / Script

One of these equal-mass carts has a spring plunger which pushes them apart. We'll tie them together with a string so they can't come apart, and balance them in the middle of this see-saw board.

If the string is burned, the carts spring apart and move off with equal and opposite velocities. The board remains balanced.

What will happen if we double the mass of one of the carts by adding this wooden block and repeat the process?

To get the board to balance initially, it is necessary to put the carts off center, so their center of mass is above the pivot point of the board. Will the board stay balanced when we burn the string?

The board stays balanced until the lighter cart strikes the end of the board.

Equipment

1. Pivot base for see-saw.
2. 6 to 8-foot length of plywood with end stops (cart containment).
3. 2 carts—one with spring loaded plunger to propel carts aparts.
4. Supply of string loops.
5. A torpedo level.
6. Source of flame.
7. 4x4 block whose mass is equal to that of one cart.