The Video Encyclopedia *of* Physics Demonstrations™

Explanatory Material By: Dr. Richard E. Berg
University of Maryland

Scripts By: Brett Carroll
University of Washington

Equipment List By: John A. Davis
University of Washington

Editor: Rosemary Wellner

Graphic Design: Wade Lageose/Art Hotel

Typography: Malcolm Kirton

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DISC ONE

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CHAPTER 1

UNITS AND VECTORS

Demo 01-01 Basic Units

The three basic quantities from which most other mechanical units are derived are mass, length, and time. Physicists commonly prefer to use the system of units known as SI (*Système Internationale* in French), or metric units. SI units for these quantities are the kilogram for mass, the meter for length, and the second for time. According to the reference volume *A Physicist's Desk Reference*,† these units are defined as follows:

meter (symbol m): "The meter is the length of path travelled by light in vacuum during the time interval 1/299,792,458 of a second."

kilogram (symbol kg): "The kilogram is the unit of mass, it is equal to the mass of the international prototype of the kilogram." (The international prototype is a platinum-iridium cylinder kept at the BIPM in Sèvres, France.)

second (symbol s): "The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom."

This video aims to help clarify the meter unit by comparing a meter stick with the commonly used yardstick, which has been marked off in units of one inch. A kilogram mass is also compared with a one-pound weight of the same material.

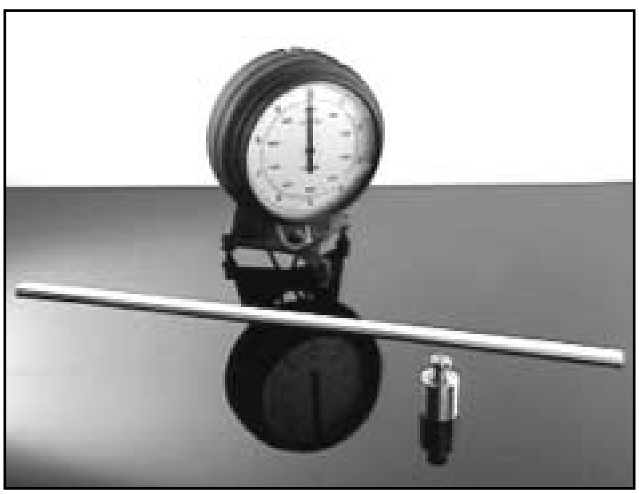

Figure 1

The conversions between SI units and common English units are:

1 m = 3.28 ft		= 39.4 in
1 ft = 0.305 m		= 30.5 cm
1 kg = 2.2 lb		
1 lb = 0.454 kg		= 454 g

† Herbert L. Anderson, Editor-in-Chief, *A Physicist's Desk Reference*, The Second Edition of *Physics Vade Mecum* (American Institute of Physics, New York, 1989), page 5.

Basic Units / Script

Physics makes use of a standard set of reference units for quantities such as mass, length, and time.

Here are examples of the standard units and their modern methods of derivation.

The standard unit of mass is the kilogram, which can be calibrated only by comparing it with a standard kilogram carefully maintained in a vault in France, or duplicates made from the standard.

The standard unit of length is the meter, which is now defined in terms of the distance light travels in a specific time interval approximately equal to one 300 millionth of a second.

For the purpose of comparison, here is the length of one yard. The standard unit of time is the second, which is defined as the time required for a precise number of periods of a type of radiation emitted by cesium atoms.

These three units combine to make up many of the other units commonly used in physics.

Equipment

1. 1-kilogram mass and a 1-pound mass to compare.
2. 1 meter stick and 1 yardstick to compare.
3. 1 clock with a 1-second sweep hand.

Demo 01-02 Vector Addition (Parallelogram)

Vector addition can be carried out either graphically or mathematically by components. This graphics demonstration illustrates the "parallelogram rule," one method by which we can add vectors.

The two vectors to be added are translated without rotation so that their tails touch, forming two sides of a parallelogram. The remaining sides of the parallelogram are then constructed parallel to the two vectors. We can then draw the vector sum of the two original vectors from the point at which the two tails touch to the corner of the parallelogram opposite that corner, as shown in *Figure 1* and on the video for several different sets of vectors.

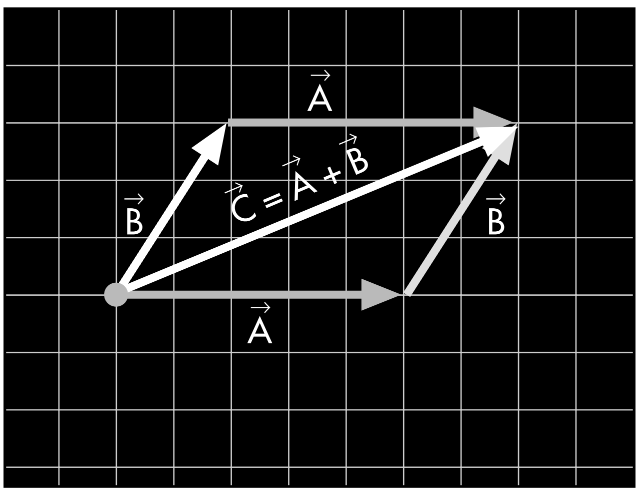

Figure 1

We'll use these animated vector arrows to demonstrate the parallelogram method of adding vectors.

The vectors are positioned with their tails together, and a parallelogram is formed by putting in lines that are parallel to and equal in length to each of the vectors. The sum of the two vectors is the vector formed by drawing a line from the tails across to the opposite corner of the parallelogram. As the angle between the vectors changes, the magnitude of their sum changes from zero to twice the magnitude of either vector.

Here is the same sequence repeated with vectors of unequal length.

Equipment

This demonstration is animated, but can be done with vector shapes mounted on magnets, which in turn adhere to a ferrous blackboard.

Demo 01-03 Vector Addition (Head to Tail)

Vector addition can be carried out either graphically or mathematically by components. This graphics demonstration illustrates graphical addition of vectors by the "head-to-tail" method. To add vectors graphically, the second vector is translated without rotation and placed with its tail at the head of the first vector. The sum is then drawn from the tail of the first vector to the head of the second vector, as shown in *Figure 1* and on the video for several sets of vectors.

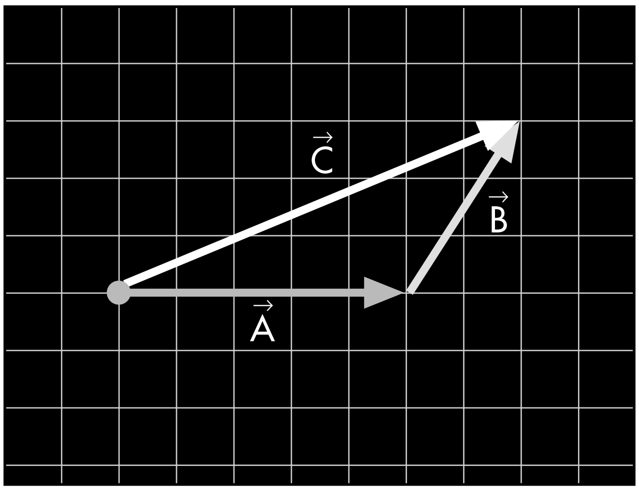

Figure 1

We'll use these animated vector arrows to show a method of vector addition called head to tail addition. If we want to add vector *B* to vector *A*, we simply move *B* so that its tail is in the same position as the head of *A*, keeping it parallel to its original orientation at all times. The sum of the two vectors is found by drawing a third vector from the tail of *A* to the head of *B*.

This is how the sum of the two vectors changes if vector *B* is rotated to different orientations. Since the two vectors are equal in magnitude, their sum can have a magnitude ranging from zero to twice that of *A* and *B*.

Equipment

See Demonstration 01-02.

Demo 01-04 Vector Components

For purposes of vector mathematics, vectors may be broken down into their components along the coordinate axes. For example, in the simple cartesian coordinate system shown in *Figure 1,* vector $\vec{A}$ has components A_x and A_y along the x and the y axes respectively. Components of an arbitrary vector are shown in the video as the vector rotates about the origin.

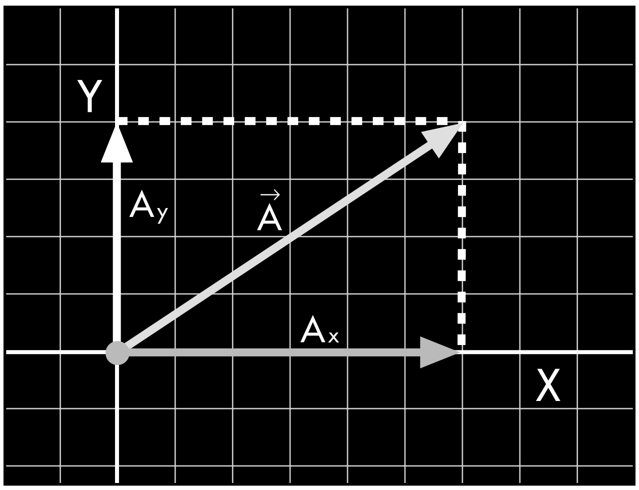

Figure 1

We'll use this animated vector arrow to show how a vector can be broken down into components, and how those components vary as the angle of the vector changes.

This vector can be broken down into two components, one along the x axis, and one along the y axis.

Here's how the components change as the vector is rotated around the origin.

Equipment

See Demonstration 01-02.

Demo 01-05 Vector Dot Product

The scalar or dot product of two vectors is defined as:

$$C = \vec{A} \cdot \vec{B} = AB \cos \theta_{AB}$$

where θ_{AB} is the angle between the two vectors, and A and B are their magnitudes. The dot product is a scalar, and has a magnitude but not a direction. When the angle between the two vectors is 90°, the dot product is zero. When the angle between the two vectors is 0°, the magnitude of the dot product is the product of the magnitudes of the vectors.

The dot product of two vectors is shown in the video as one vector rotates while the other one remains at a constant orientation.

One of the more important examples in physics using the dot or scalar product is work.

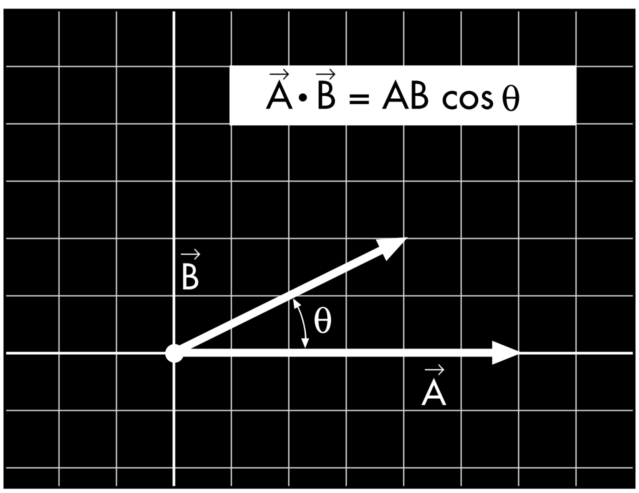

Figure 1

The dot product of two vectors is a scalar quantity which is equal to the product of their magnitudes times the cosine of the angle between them.

We'll use these animated vectors to show how the dot product of two vectors varies as the angle between the vectors changes.

Equipment

This demonstration is an animation.

Demo 01-06 Vector Cross Product

The vector or cross product of two vectors is defined as:

$$\vec{\boldsymbol{C}} = \vec{\boldsymbol{A}} \times \vec{\boldsymbol{B}} = AB \sin \theta_{AB} \hat{c}$$

where θ_{AB} is the angle between the two vectors and A and B are their magnitudes. Notice that $\vec{C}$ is a vector with the direction of the unit vector $\hat{c}$, perpendicular to the plane of A and B. The direction of the cross product can be obtained as follows: rotate a right-handed (standard) screw such that it rotates from the vector $\vec{A}$ to the vector $\vec{B}$ through the smaller of the two angles between them. The screw will then drive in the direction of the cross product vector. Equivalently, if you curl the fingers of your right hand in the direction from $\vec{A}$ to $\vec{B}$ through the smaller of the angles between the vectors, your thumb will point in the direction of the vector product.

Another variation of the right hand rule for vector cross product is illustrated in *Figure 1*: Using the fingers on your right hand, if the index finger points in the direction of vector $\vec{A}$ and your middle finger points in the direction of vector $\vec{B}$, then the thumb will point in the direction of the cross product $\vec{C}$.

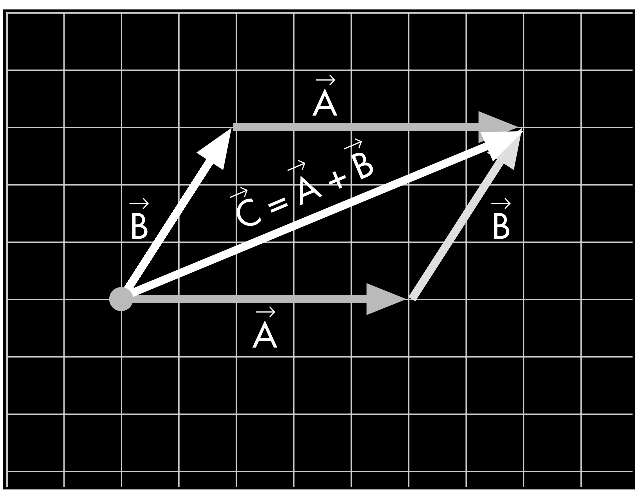

Figure 1

When the angle between the two vectors is either 0° or 180°, the cross product is zero. When the angle between the two vectors is 90°, the magnitude of the cross product is the product of the magnitudes of the two vectors.

The cross product of two vectors is shown in the video as one of the two vectors rotates around the origin while the other remains fixed.

Examples of the cross product in physics include torque and the magnetic force on a moving charged particle.

We'll use these animated vector arrows to show how the cross product of two vectors varies as the angle between them is changed.

The cross product of these two vectors, A and B, is a vector at right angles to both. Its direction can be found using the right-hand rule.

The magnitude of a cross product of two vectors is equal to the product of their magnitudes times the sine of the angle between them.

Here's how the cross product of A and B changes as the angle between them is changed.

Equipment

This demonstration is an animation.

Demo 01-07 3-D Vector Components

This demonstration extends the vector concept of Demonstration 01-04 to three dimensions. The video shows several vectors in three dimensions on an *x-y-z* cartesian coordinate system of axes.

The orientation of the vector is now defined by three angles, the angles between the vector and each of the three axes. Notice that the angle between the vector and any axis is not the same as the projection of that angle on any one of the three planes containing two axes.

The apparatus used in the demonstration is shown in *Figure 1,* viewing along the *x* axis, so that the *y* and the *z* components are apparent.

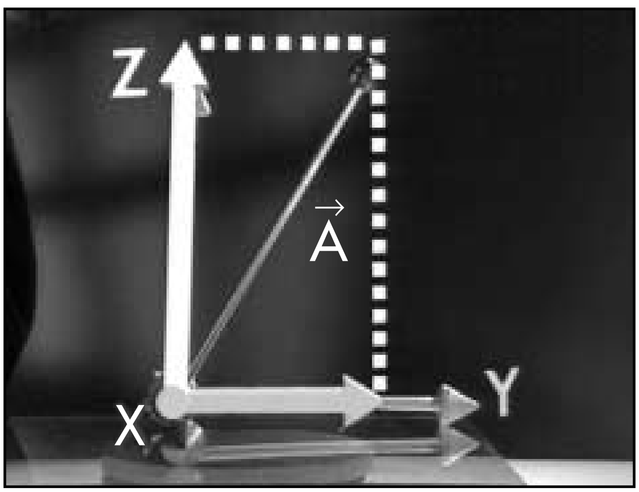

Figure 1

This metal frame is a model of a three-dimensional coordinate system, with x, y, and z axes.

A vector that is anchored at the origin is free to move in the volume defined by the three axes.

We'll move it to different positions in the frame and look at the model along each of the three axes to show the components of the vector on those axes.

When we look along the z axis, we see the components of the vector in the x and y axes.

Looking along the y axis shows the components along the x and z axes.

Looking along the x axis shows the components along the y and z axes.

Now we'll change the position of the vector in the frame and repeat the sequence.

Equipment

A model vector coordinate system with a resultant vector that is free to move in space is used for this demonstration.

Chapter 2

LINEAR KINEMATICS

LINEAR KINEMATICS

The demonstrations in this chapter have been chosen primarily to illustrate the concepts of motion with constant velocity and motion with constant acceleration, including the addition of velocities along a line.

For the case of constant acceleration *a,* the velocity v can then be determined as a function of time t †

$$v(t) = v_0 + at$$

where the initial velocity is v_0 at time $t = 0$. The position x as a function of time is then

$$x(t) = x_0 + v_0 t + \frac{1}{2} a t^2$$

where the initial position is x_0 at time $t = 0$.

An additional useful relationship can be derived between the position and the velocity:

$$v^2(t) - v_0^2 = 2a\left(x - x_0\right)$$

For the simplified case of motion starting with $x = 0$ at time $t = 0$ and zero velocity, these equations simplify to:

$$v(t) = at$$

$$x(t) = \frac{1}{2} a t^2$$

$$v^2(t) = 2ax$$

† These equations are discussed in detail in several physics texts, for example, Halliday, Resnick, and Walker, *Fundamentals of Physics*, Extended Fourth Edition, Chapter 2, Sections 1–7.

Demo 01-08 Constant Velocity

This demonstration illustrates constant velocity using an air track glider. For the case of constant velocity, the distance traveled by the glider in equal time intervals is the same, which can be seen by marking the position of the glider on the video screen at a series of equal time intervals.

Each end of the air track is fitted with spring bouncers. This ensures that the glider collides elastically with the end of the air track, so that its speed is the same but its direction is reversed, changing the velocity vector from $+\vec{v}$ to $-\vec{v}$.

Figure 1

We'll float this glider on a cushion of air to reduce the friction which normally slows down moving objects. After the glider is pushed, it moves smoothly down the track until it hits the bumper at the end.

These dots will track the motion of the glider every half second to record the glider's position vs. time. What does the spacing of the dots tell us about the glider's velocity?

Since the spacing between dots is constant, the velocity of the glider must be constant. What happens to the velocity when the glider strikes the end of the track?

As this vector representation shows, when the glider strikes the end the velocity is reversed in direction, but the magnitude, or speed, is the same. Here is the glider moving at a higher velocity.

Equipment

1. Level air track.
2. Blower system.
3. Heavy glider.

Demo 01-09 Bulldozer on Moving Sheet

This experiment demonstrates addition and subtraction of velocities along a line using two toy bulldozers and a paper sheet.† One bulldozer moves with a constant velocity v_1 over the table. The second bulldozer moves with the same constant velocity v_1 on a paper sheet that can be moved along the same line as the velocity of the bulldozer. This arrangement is shown in *Figure 1*.

If the paper sheet remains at rest, the two bulldozers move along together in the same direction at velocities of v_1. If the paper sheet is pulled with a velocity v_2 in the same direction as the bulldozer, the velocity of the bulldozer in the laboratory frame of reference will increase to $v_1 + v_2$. If the paper sheet is pulled with the same speed in the opposite direction, the velocity of the bulldozer in the laboratory frame will decrease to $v_1 - v_2$.

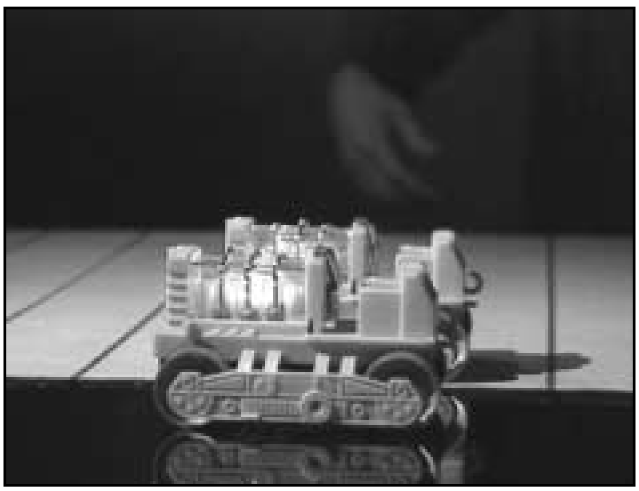

Figure 1

† Freier and Anderson, *A Demonstration Handbook for Physics*, Demonstration Mb-30, Relative Velocity.

We'll use this pair of toy bulldozers, which run at constant speed, to demonstrate how velocities add and subtract.

This bulldozer is running on a stationary tabletop.

A second bulldozer which runs at the same velocity is placed next to the first, but on top of a paper sheet which can also be moved at a constant velocity.

If we move the sheet along the table in the same direction as the bulldozers, how will the velocity of the second bulldozer compare with the bulldozer on the table?

When the sheet moves in the same direction as the bulldozer moves, the velocity of the sheet is added to that of the bulldozer so it runs faster than the one on the table. If we move the sheet in the opposite direction as the bulldozer, its velocity relative to the table is decreased.

Equipment

1. Two battery-powered toy bulldozers.
2. Long sheet of paper or plastic with evenly spaced grid markings.
3. Rollers for sheet if desired—can be held by hand.

Demo 01-10 Rolling Ball Incline

In this demonstration a ball is rolled down an incline, illustrating motion with a constant acceleration. Lights located at carefully chosen points along the incline flash once per second, marking the position of the ball at one-second intervals.† The system is set up so that the first flash occurs at time $t=0$, just as the ball is released. *Figure 1* is a graph of position x versus time t for the rolling ball. By taking the difference between positions for two successive one-second time intervals, we obtain the mean speed of the ball as a function of time and plot it in *Figure 2*. Using measured $x(t)$ values at time intervals of one second,

$$\Delta x_1 = x(1) - x(0) = x(1) \qquad v_1 = \frac{\Delta x_1}{1s}$$

$$\Delta x_2 = x(2) - x(1) \qquad v_2 = \frac{\Delta x_2}{1s}$$

$$\Delta x_3 = x(3) - x(2) \qquad v_3 = \frac{\Delta x_3}{1s}$$

$$\Delta x_4 = x(4) - x(3) \qquad v_4 = \frac{\Delta x_4}{1s}$$

Taking the difference between speeds for two successive one-second intervals, we obtain the acceleration as a function of time and plot it in *Figure 3*.

$$\Delta v_1 = v_2 - v_1 \qquad a_1 = \frac{\Delta v_2}{1s}$$

$$\Delta v_2 = v_3 - v_2 \qquad a_2 = \frac{\Delta v_3}{1s}$$

$$\Delta v_3 = v_4 - v_3 \qquad a_3 = \frac{\Delta v_4}{1s}$$

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-77, Timed-interval Inclined Plane, page 39.

When plotting the values of x and v versus t, we take care to plot each value at the center of the time interval covered. Thus v_1 is plotted at $t = ½s$, v_2 is plotted at $t = 1½s$ and so forth; a is plotted at $t = 1s$, a_2 is plotted at $t = 2s$, and so forth, as indicated in *Table I.*

For this case the acceleration a is constant, so the velocity v increases linearly with time,

$$v = at$$

and the position of the ball increases quadratically with time, so the position versus time graph is a parabola:

$$x = \frac{1}{2}at^2$$

Table I

t (sec)	x (units)	v (units/s)	a (units/s^2)
0.0	0		
0.5		1	
1.0	1		2
1.5		3	
2.0	4		2
2.5		5	
3.0	9		2
3.5		7	
4.0	16		

Equipment

1. Inclined track with lights positioned at one, four, nine, sixteen, and twenty-five units, equipped with a ball catcher at far end of track.
2. A timing/release mechanism to permit the ball's rolling descent to begin at the same moment that the lights flash in unison.
3. A steel ball.
4. Magnetic strips of appropriate lengths to show all d's, Δd's, and Δv's.
5. Ferrous background for graphic display of strips.

Rolling Ball Incline

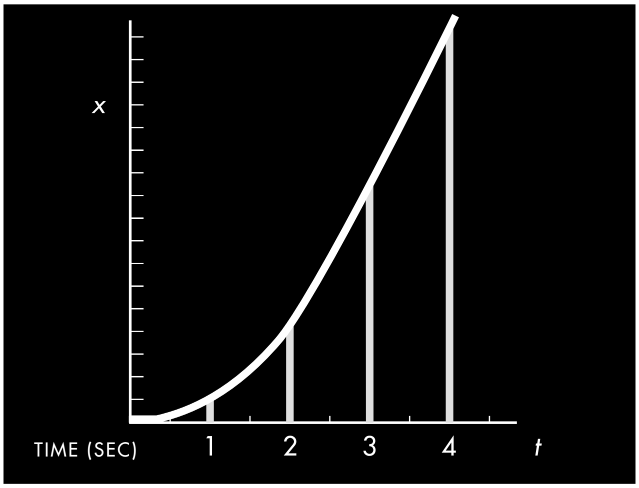

Figure 1

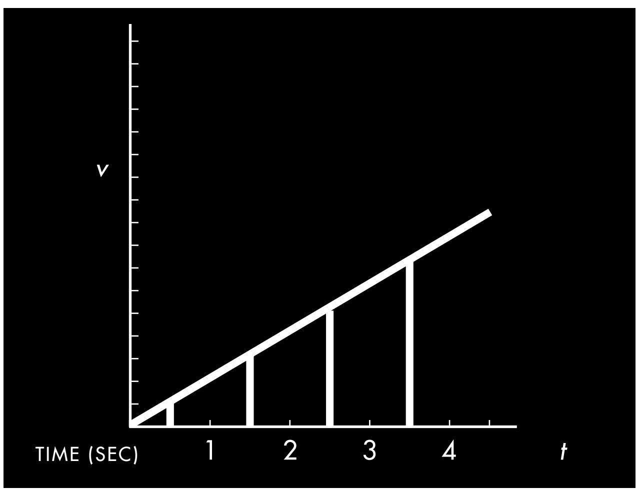

Figure 2

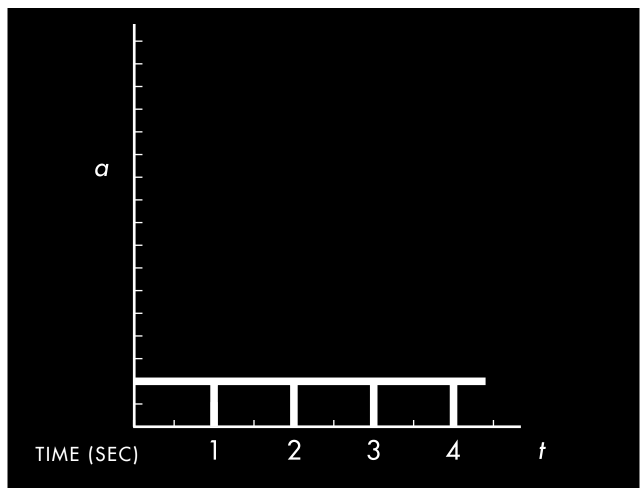

Figure 3

A ball rolling down a long incline will be used to show how position, velocity, and acceleration of the ball change as it moves down the incline.

Five lights arranged along the length of the track flash simultaneously once per second.

As the ball rolls down it is directly above each of the lights just as they flash. This gives us a record of the positions of the ball at one-second intervals.

This is how far the ball traveled in the first second.

This is how far the ball traveled in the first two seconds.

Three seconds.

Four seconds.

We will move this distance up to a graph to keep track of position vs. time.

Does position change linearly over time?

Next we will graph the average velocity of the ball during five different intervals to see how velocity varies as the ball rolls down the incline. The ball moved this far during the first second.

It moved this far during the next second.

This far during the third second.

The fourth second.

This gives us a graph of the velocity of the ball over time. Does velocity increase linearly?

Now we will graph the changes in velocity vs. time by graphing the differences in successive velocities.

What does this tell us about the acceleration of the ball?

The acceleration is constant.

Demo 01-11 Constant Acceleration

In this demonstration an air track is tilted to provide constant acceleration of the glider. By marking the position of the glider at a series of equal time intervals, we can obtain the value of the acceleration using a technique similar to that of Demonstration 01-10.

For actual measurements the position of the glider can be measured directly or you may use its position at one-half second intervals, as shown in the video. In this case the acceleration *a* is

$$a = g \sin\theta$$

where *g* is the acceleration of gravity and θ is the angle the air track makes with respect to the horizontal. Therefore, the linear speed *v* of the glider is

$$v = at = (g \sin\theta)t$$

and the position ***x*** as a function of time is

$$x = \frac{1}{2}at^2 = \frac{1}{2}(g \sin\theta)t^2$$

The three angles at which the air track is tilted for the cases shown in the video are 0.70°, 1.15° and 1.60°.

Figure 1

We will use a nearly frictionless air track with a glider floating on an air cushion to demonstrate accelerated motion.

When the track is level, a push is required to move the glider. It then moves at a constant velocity as shown by these dots that track the position of the glider at half-second intervals.

When we tilt the track by placing a 1-centimeter high shim under one end, the glider moves down the track.

What can we say about the magnitude of the velocity in this case?

The glider's velocity increases with time—it accelerates. If we increase the tilt of the track by doubling the height of the shim, the acceleration increases.

When the shim height is increased to 3 centimeters, the acceleration increases again.

This split-screen view shows the glider accelerating at all three angles of tilt.

Equipment

1. Level air track.
2. Blower system.
3. Heavy glider.
4. Multiple spacing shim to incline track.

Demo 01-12 String and Weights Drop

In this demonstration the geometrical nature of the distance versus time curve for the case of constant acceleration is shown.† Two strings are dropped vertically, one with weights attached at equal intervals and one with weights attached at intervals spaced geometrically, as shown in *Figure 1*. By listening to the time sequence with which the weights hit the floor, we can verify that the distance versus time curve for falling bodies under the constant acceleration of gravity is a parabola.

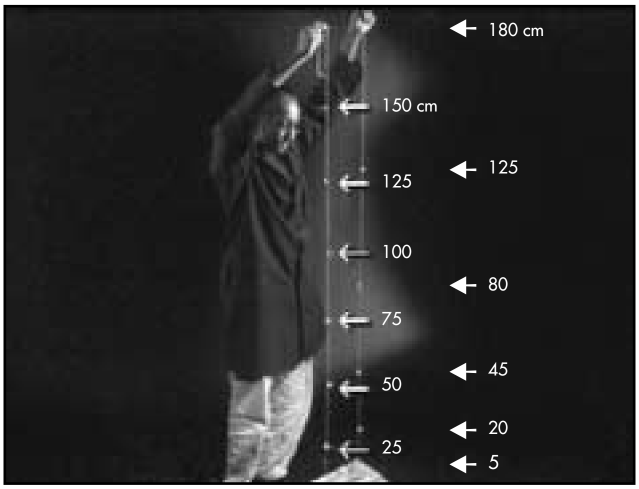

Figure 1

In the case of constant acceleration of gravity g,

$$a = g$$

the velocity versus time for freely falling bodies is

$$v = gt$$

and the distance versus time is

$$s = \frac{1}{2}gt^2$$

so

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

For the case of weights attached at equal distances along the string, the intervals between times when the weights hit the floor are shown in *Table I.* For the case of weights attached at distances along the rope in ratios of 1:4:9:16:25 the intervals between times when the weights hit the floor are equal, as shown in *Table II.*

† Sutton, *Demonstration Experiments in Physics*, Demonstration M-84, Freely Falling Bodies. Meiners, Physics *Demonstration Experiments*, Section 7-1.12, Freely Falling Bodies, page 113. Freier and Anderson, *A Demonstration Handbook for Physics*, Demonstration Mb-12, Time Intervals of Fall.

String and Weights Drop — *Demo 01-12*

Table I

s (cm)	t (s)	Δt (s)
0	0.000	
25	0.226	0.226
50	0.319	0.093
75	0.391	0.072
100	0.452	0.061
125	0.505	0.053
150	0.553	0.048

Table II

s (cm)	t (s)	Δt (s)
0	0.000	
5	0.101	0.101
20	0.202	0.101
45	0.303	0.101
80	0.404	0.101
125	0.505	0.101
180	0.606	0.101

String and Weights Drop / Script — *Demo 01-12*

On the left is a string with small weights tied at regular increasing heights above the ground. We'll drop the string and listen to the sound as each weight strikes a board at the bottom.

When the string is dropped, the weights strike the board in decreasing intervals of time.

On this string, the height of the weights increases geometrically.

When this string is dropped, the weights strike the board at equal intervals of time.

Equipment

1. A string tied with equally spaced weights.
2. A string tied with weights with geometrically increasing spacing.
3. A board on which one can drop the two series of weights and utilize the emitted sound to judge the time intervals of the weights striking the board.

Demo 01-13 Reaction Time Falling Meter Stick

In this demonstration a meter stick is used to determine the reaction time of a human subject.† The experimenter holds the meter stick vertically by the top end with the subject's hands even with the 50-cm mark on the meter stick, ready to catch the meter stick when it is dropped, as shown in *Figure 1*. The experimenter then drops the meter stick. The distance the meter stick falls before it is caught by the subject is used to determine the reaction time of the subject.

The equation relating distance and time for the case of free fall is

$$s = \frac{1}{2}gt^2$$

so after observing how far the meter stick fell, the reaction time can be calculated as

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

If the tops of the subject's hands are initially aligned with the 0-cm end mark of the meter stick, s can be read directly off the meter stick, and converted to time using *Table I*.

Figure 1

Reaction Time Falling Meter Stick

Demo 01-13

Table I

s (cm)	*t* (ms)	*s* (cm)	*t* (ms)	*s* (cm)	*t* (ms)	*s* (cm)	*t* (ms)
1	45	14	169	27	235	40	286
2	64	15	175	28	239	41	289
3	78	16	181	29	243	42	293
4	90	17	186	30	247	43	296
5	100	18	192	31	252	44	300
6	111	19	197	32	256	45	303
7	120	20	202	33	260	46	306
8	128	21	207	34	263	47	310
9	136	22	212	35	267	48	313
10	143	23	217	36	271	49	316
11	150	24	221	37	275	50	319
12	156	25	226	38	278		
13	163	26	230	39	282		

Reaction Time Falling Meter Stick / Script

Demo 01-13

When a meter stick is dropped, the distance it has fallen increases with time. We'll use that fact to measure the time it takes a person to react after a meter stick is dropped.

One person holds a meter stick vertically while a second person waits with her fingers poised at the 50-centimeter mark on the stick. The stick will be dropped unexpectedly and the second person will try to catch it as quickly as possible.

The distance the stick falls before it is caught will show how quickly the second person reacted after the meter stick was released.

This is how far the meter stick fell before it was caught. What is this person's reaction time?

Equipment

1. Meter stick.
2. Two demonstrators; one to drop, one to catch.

Demo 01-14 Guinea and Feather

This is the classic demonstration showing that the acceleration of free fall is independent of mass, in the absence of other significant forces such as air friction.† A metal disc and a small piece of paper are placed inside two identical vertical glass tubes, and the tubes are rapidly rotated so the objects remain stuck at one end. When the tubes are upside down, the disc and the paper begin to fall to the lower end. Due to air drag the paper falls more slowly than the disc. When the air is pumped out of the tube, the disc and the paper fall with the same acceleration and reach the bottom end of the tube at the same time.

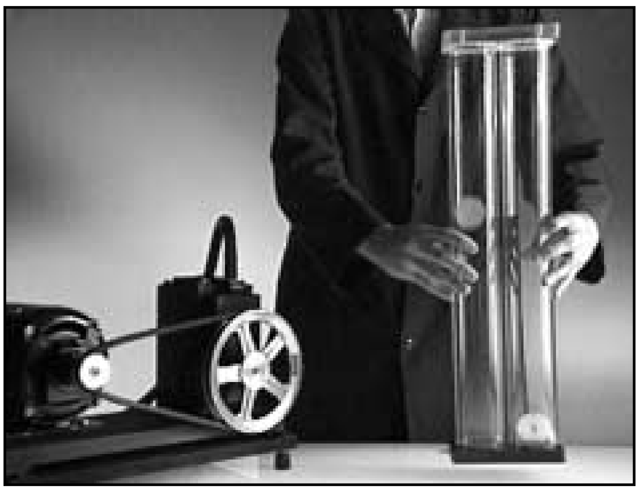

Figure 1

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-79, Guinea-and-Feather Tube.

We are used to seeing light objects fall more slowly than heavy objects. But why do light and heavy objects fall differently?

We will use this pair of tubes containing metal and paper discs to show the effect of eliminating air resistance. This is how the objects fall when the tubes are filled with air.

If we now remove most of the air from the tubes with a vacuum pump and repeat the demonstration, the results change dramatically.

Equipment

1. Guinea and feather tube—sealed and equipped for evacuation.
2. Vacuum pump.
3. Perhaps a light and heavier object to drop through open atmosphere as a comparison.

Chapter 3

LINEAR DYNAMICS

Demo 01-15 String and Weight Acceleration

This experiment, sometimes called a horizontal Atwood's machine, involves acceleration of an air track glider by a small mass attached to the glider by a string passing over a pulley.†

The gravitational force on the small hanging mass provides the force to accelerate the glider, as seen using the free body diagram of *Figure 1*, giving the equations:

$$mg - T = ma$$

$$T = Ma$$

where T is the tension in the string, M is the mass of the glider, m is the mass of the small hanging mass, a is the acceleration of the system, and g is the acceleration of gravity. The acceleration a of the system can then be obtained by eliminating T:

$$a = \frac{m}{M + m} g$$

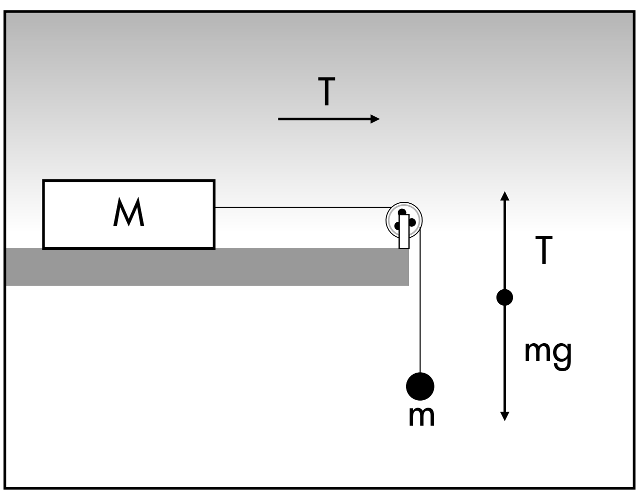

Figure 1

Like the standard Atwood's machine, the system thus moves with a constant acceleration. The acceleration of the system can be determined experimentally using the difference method of Demonstration 01-10.

Three cases are shown in the video:
(1) glider mass M with accelerating mass m.
(2) glider mass M with accelerating mass $2m$.
(3) glider mass $2M$ with accelerating mass m.

If $m < M$, the acceleration becomes

$$a \approx \frac{m}{M} g$$

so, to a good approximation, relative to the original case (1) the acceleration will double for case (2) and halve for case (3).

For the experiment shown on the video, the accelerating mass m = 3.3 grams and the glider mass M = 200 grams.

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-108, Acceleration on a Horizontal Plane, page 50.

If a string hanging over a pulley is loaded with a small weight, it provides a force which can accelerate a glider floating on a cushion of air.

Here is the same acceleration, with the position of the glider marked by dots at half-second intervals.

If the force is doubled by doubling the hanging mass, how will that affect the acceleration of the glider?

The dots are more widely spaced, so the acceleration has increased.

If the same hanging weight is now used but the glider's mass is doubled, how will the acceleration change?

Here is the new acceleration.

Here are all three accelerations and the force and mass data for each.

Equipment

1. Level air track.
2. Blower system.
3. Glider.
4. Two low-friction pulleys.
5. Very lightweight length of string.
6. A supply of paper clips.
7. Support system for pulleys.
8. Appropriate masses to double the glider's weight.
9. Perhaps a stopwatch to measure the time of fall.

Demo 01-16 Atwood's Machine

The classical Atwood's machine,[†] consisting of two masses hanging on a light string over a light, frictionless pulley, is used to study force and acceleration. If the masses are nearly equal, the motion may be slow enough that accurate measurements can be made. We can do this by using large masses on each side and increasing the mass on one side by adding a smaller rider.

For such a system, shown in *Figure 1*, we can formulate the equation of motion by considering the free-body drawings for each side.

$$(M+m)g = T + (M+m)a$$

$$Mg = T - Ma$$

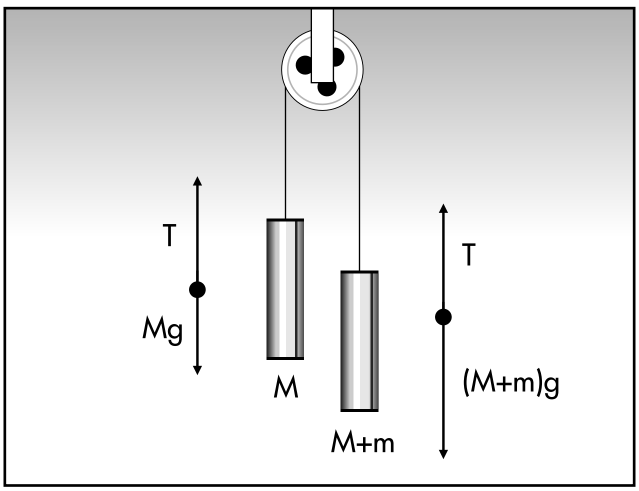

Figure 1

where M is the larger mass on each side, m is the lighter mass of the rider, T is the tension in the string, a is the acceleration of the system, and g is the acceleration of gravity. Eliminating T, the equation of motion is

$$a = \frac{m}{2M+m} g$$

Thus the two-mass system will move with a constant acceleration, with the side with the rider moving downward.

We can determine this acceleration experimentally by using the difference method discussed in detail in Demonstration 01-10, where the position of either weight can be measured at a series of equal time intervals. A 10-cm grid is provided at the right of the Atwood's machine for determination of the vertical scale.

In the video the net weight m is removed while the system is accelerating, causing the acceleration to cease and resulting in constant velocity for the system after that point. This can also be verified experimentally by determining the position of either weight at equal time intervals after the small net weight is removed.

† Sutton, *Demonstration Experiments in Physics,* Demonstration M-110, Atwood's Machine, pages 50-51.
Meiners, *Physics Demonstration Experiments,* Section 8-1.4, page 137.

This device is known as an Atwood's machine.

Two equal masses hang on either side of a string passing over a pulley. Since the masses are equal, there is no net force to accelerate the masses and they are in equilibrium in any position.

A small rider is now added to one of the large masses, and the system begins to move.

How could we best describe this type of motion?

Since there is a constant unbalanced force on the system, it is accelerated.

The traces left behind each half-second in this segment show the acceleration.

If the mass now passes through this ring so that the rider is picked off, how will the motion of the masses be affected?

The masses now move with a constant velocity.

Here is the same sequence repeated with two riders added to the large mass.

Equipment

1. A very low-friction pulley.
2. Lightweight length of string.
3. Two masses of equal weight.
4. Two relatively small rider weights to take the system out of static balance.
5. A catch system for the riders so that they are lifted off without disturbing the linear downward motion.
6. A stopwatch/clock.
7. A two-meter stick.

Demo 01-17 Acceleration with Spring

The horizontal Atwood's machine and the Atwood's machine (Demonstrations 01-15 and 01-16) are two devices that apply a constant force to a system to produce constant acceleration. A third technique is illustrated in this demonstration.

A flexible spring is attached to the front of an air track glider, and the glider is pulled along the track so that the spring remains stretched to a constant length as shown in the video, and in *Figure 1.*

Figure 1

We will use a glider floating on a cushion of air and a light spring to demonstrate how a constant force from a spring can accelerate the glider.

The spring is attached to the end of the glider, and a marker stick is attached to the top of the glider to indicate the extension of the spring.

When the spring is pulled out, it pulls on the glider with a constant force. The force from the spring accelerates the glider. Here is the same acceleration repeated, with dots on the screen recording the position of the glider every half second.

Equipment

1. Level air track.
2. Blower system.
3. Heavy glider with extended marker bar.
4. Two low-friction pulleys.
5. Very lightweight spring with a small spring constant.

Demo 01-18 Dropped Slinky

A Slinky spring is held by one end and allowed to hang freely in a line directly under the point of support. If it is released from rest, what will the Slinky do? Will the entire Slinky accelerate down? Will the bottom end of the Slinky begin to accelerate downward, accelerate upward, or remain at the same position?

The Slinky spring begins to fall downward immediately after it is released, simultaneously shrinking due to the internal forces, which are no longer balanced by the force of the hand holding the Slinky and the force of gravity.

The motion of the collapsing Slinky has been recorded on high-speed film, and is presented in slow motion so that the details of the collapse mechanism can be studied.

Figure 1

Dropped Slinky / Script

When this spring is held at the top and allowed to hang, the weight of the spring stretches it out. If we release the spring, its weight will still be pulling on it during the fall. What will happen to the length of the spring during the fall?

The spring immediately contracts when it is dropped.

Equipment

One Slinky.

Demo 01-19 Candle in Dropped Jar

This demonstration illustrates the state of apparent weightlessness in free fall in the earth's gravitational field. When a candle burns, it is dependent on rising convection currents in the air around it to carry the hot combustion products up away from the candle and deliver new air with oxygen from below to the burning wick, as illustrated in *Figure 1*. Convection currents are dependent on gravity because the hotter combustion products are also lighter than the surrounding air and therefore will rise due to their buoyancy in the more dense air.

A candle is placed inside a sealed jar containing enough air to keep the candle burning for a relatively long time. However, when the jar is dropped, and falls freely with the acceleration of gravity, the candle immediately goes out.[†] In the frame of reference of the falling jar a state of apparent weightlessness exists, causing convection currents to cease and removing the supply of oxygen to the flame.

This is true weightlessness according to General Relativity.

Figure 1

† Sutton, *Demonstration Experiments in Physics*, Demonstration M-98, Freely Falling Candle, page 46.
Bassam Z.Shakhashiri, *Chemical Demonstrations—A Handbook for Teachers of Chemistry* , Volume 2, Combustion of a Candle in Air, Section 6-13, pages 158-161.
Meiners, *Physics Demonstration Experiments,* Section 8-3.7, page 146.

If we light a candle and place it inside a glass jar, there is enough oxygen in the jar to let the candle burn for over 10 seconds.

Moving the jar rapidly from side to side does not have a great effect on the flame because the jar protects the flame from the wind caused by the motion. But what will happen if we relight the candle and drop the jar from a height of ten feet?

The flame goes out on the way down. When the jar is in free fall, there are no convection currents to bring fresh oxygen up into the flame.

Equipment

1. Quart jar.
2. Candle affixed to inside surface of jar's lid.
3. Source of flame.
4. Catching device to protect glass jar.

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