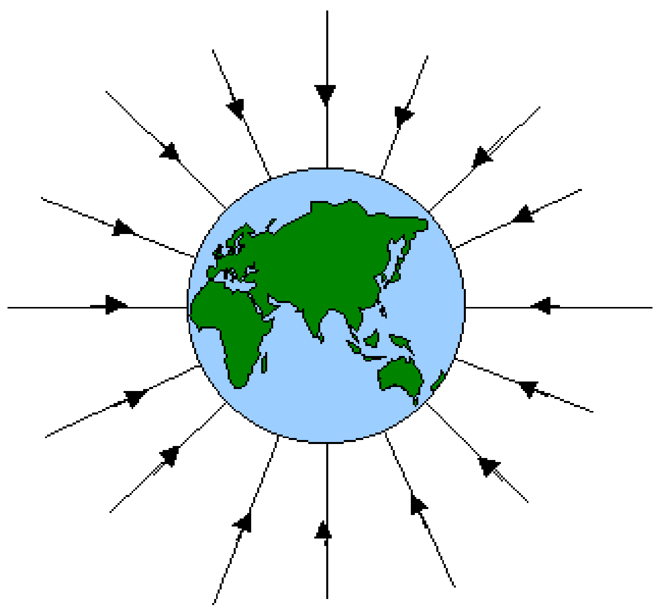
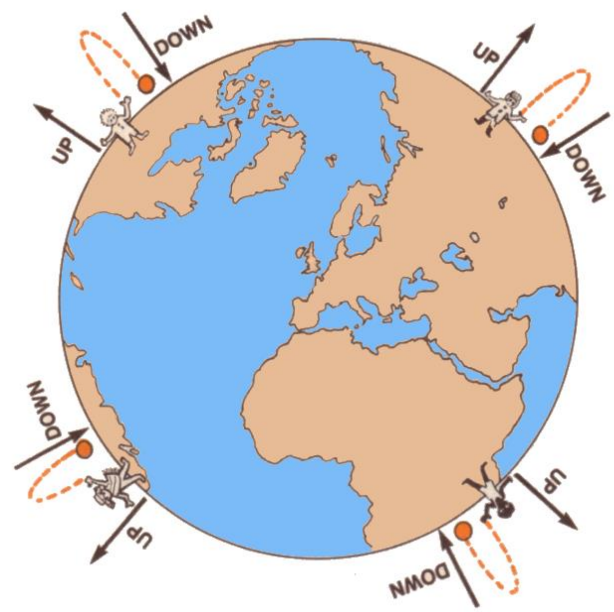
Name: ____ Date: _______

PHYSICS
UNIT 3: APPLIED FORCES & GRAVITY

VERTICAL MOTION & FALLING OBJECTS





Objects within a planet's gravity field experience being pull downward toward the planet's surface because of the mutual attraction between the object and the planet. The net movement of objects is down because of their miniscule inertia. The planet's gravity is omnipresent and affects all objects equally in the absence of air resistance's effects or other opposing forces. The downward acceleration of any body within Earth's gravity field is g $\approx 9.81\ m/s^2$. Regardless of where an object is relative to the Earth, the gravitational attraction between the object and Earth will cause downward acceleration of the object. The Earth, being the vastly more massive object has a vastly large inertia, and will remain stationary. The gravity field of Earth or any large solar system body is more-or-less uniform on all sides. All objects on all sides of the Earth are accelerated downward equally.

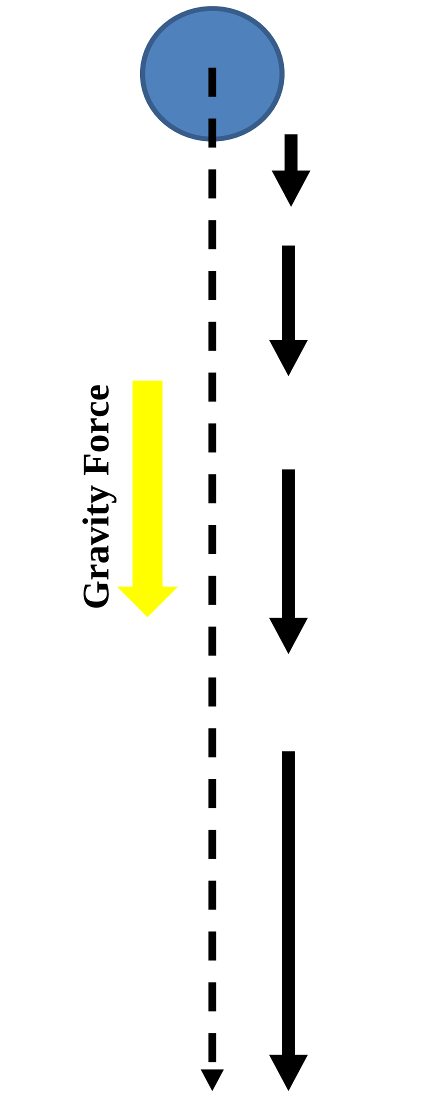
Falling Objects: Falling Down

Freefall is the natural downward motion of falling objects under the influence of gravity. Freefall is one type of vertical motion. In the absence of all other forces (e.g., air resistance, friction, wind) on Earth, objects will naturally freefall downward toward the Earth's surface and get progressively faster with increasing drop distance.

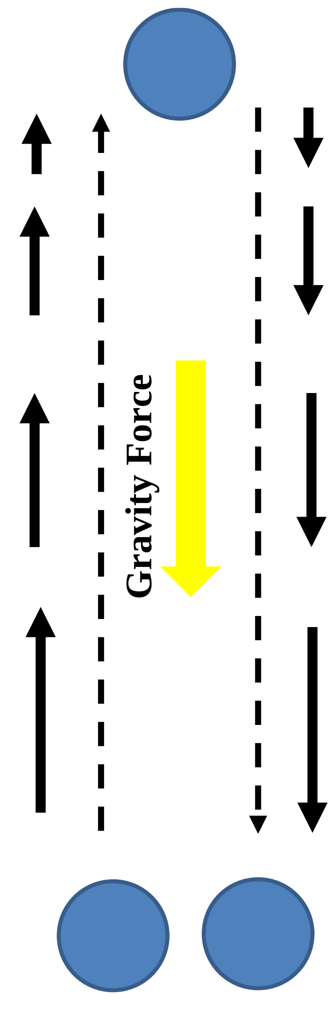
The downward acceleration in Earth's gravity field is g = 9.81 m/s^2. This means that for every 1 second that an object freefalls (without interference from other forces) the object's downward velocity increases by -9.81 m/s. Masses of objects are irrelevant. All objects in Earth's gravity field accelerate downward equally. The falling object will get progressively faster and faster with fall time.

Remember from the acceleration lesson: If a net force acts upon an object in the same direction that the object initially moves, the object will get faster with time. In the case of a falling object, it is moving in the downward direction. The gravity force acting upon the object is also in the downward direction. Therefore, the object will get faster with time.

The vector diagram shows the velocities of the falling object represented as arrows. Starting from motionless, the falling object accelerates by getting faster as it drops. The falling object moves the fastest at the instant it impacts the ground because it fell the farthest. This is the ideal case because it assumes no other external forces, like air resistance, is acting upon the falling object. It is the pure effect of gravity.



Vertical Motion: Up and Down



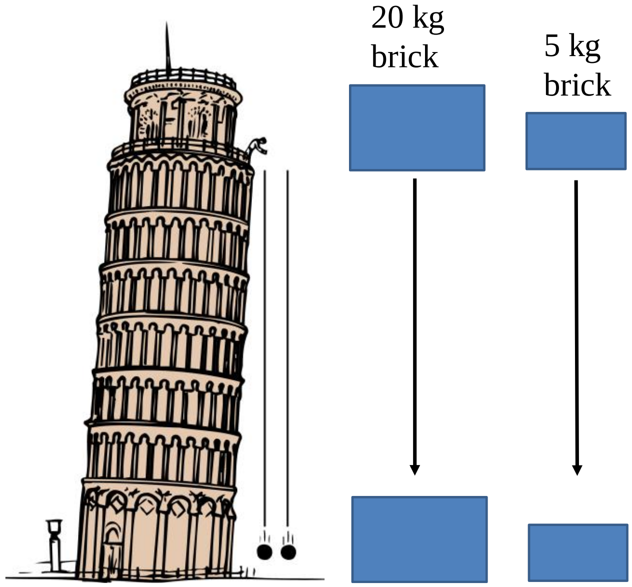
Vertical projectile motion is the other type of **vertical motion**. An object is launched or thrown upwards into the air, reaches a maximum height, changes direction, then falls to the ground. The projectile's starting and ending heights may or may not be at the same position. There is no horizontal motion—only up and down.

The downward acceleration in Earth's gravity field is g = 9.81 m/s^2. Earth's gravity accelerates the projectile in the down direction at all points as it moves through the air, resulting in its characteristic motion.

Remember from the acceleration lesson: If a net force acts upon an object in the opposite direction that the object initially moves, the object will get slower with time. As the object moves upward, its upward velocity will get slower and slower because it is being accelerated downward. After reaching the maximum height above the ground, the object will then fall down, and get faster and faster with drop distance as seen in the freefalling object.

The vector diagram shows the velocities of the vertical projectile represented as arrows. It moves the fastest in the up direction at launch, and slows as it moves upward (acceleration is down). At the highest position above the ground, it is instantaneously motionless and changes direction. It falls downward and gets faster in the down direction (acceleration is down), reaching its fastest downward speed at impact with the ground.

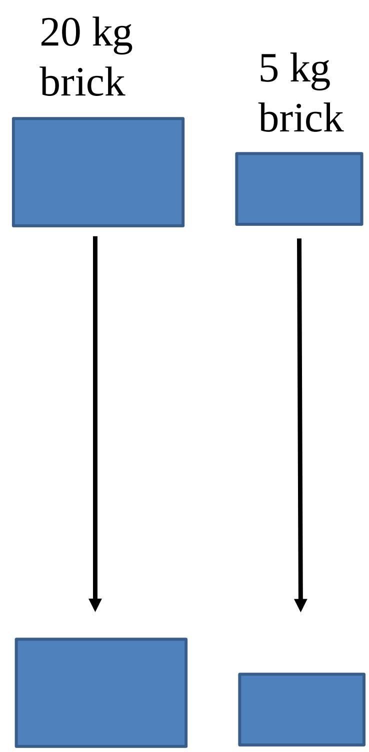
Properties of Falling Objects



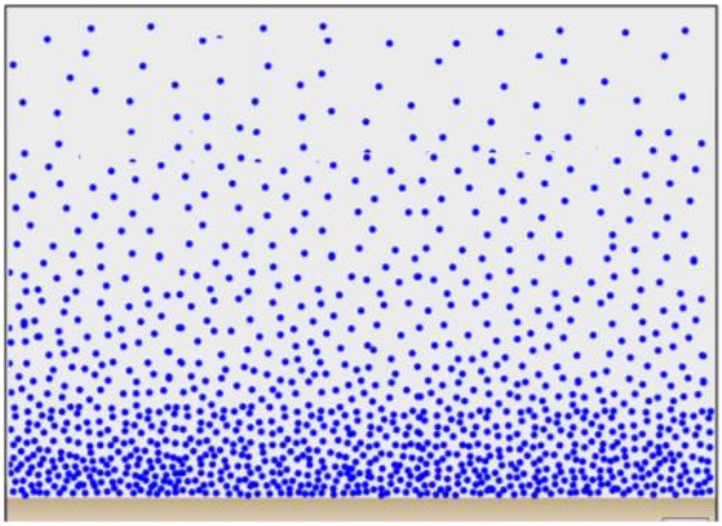
Galileo Galilei demonstrated that if two objects of comparable sizes and shapes (smooth spheres), but greatly differing masses (5 kg vs. 20 kg), are released at the same time from the same height above the ground, they should impact the ground at the same time. He explained that the two objects of different mass accelerated at the same rate. In other words, they got faster and faster at the same rate as they fell—and that mass was independent of their motion.

Illustrative Example 1

Similar to Galileo's experiment. As a generality, if two objects of similar size, similar shape, and similar density are dropped from the same height above the ground at the same time, but with different masses, both objects will impact hit the ground at the same time. The reason this happened is because air resistance affected the objects equally.



The two bricks are similar in size, shape and density. One brick is clearly more massive than the other. But they will fall and accelerate at the same rate and impact the ground at the same time. Air flow around the bricks is identical, so air resistance affects them equally as they fall.



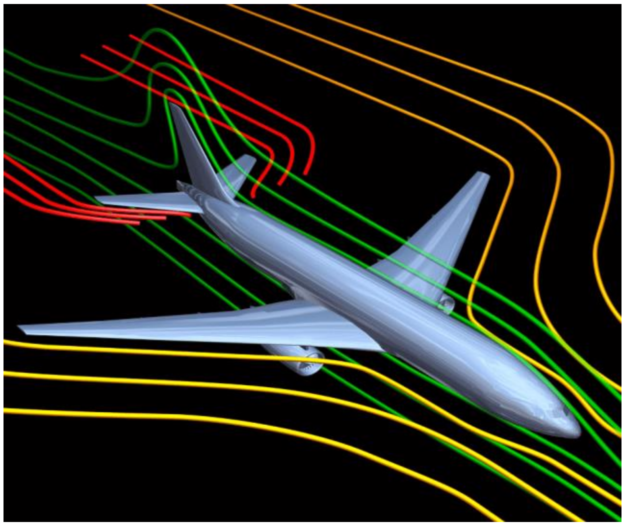
Because our atmosphere is composed of air (a gas mixture), air resistance will surely affect the downward motion of freefalling objects or the motion of any object through air. Air resistance is a resisting force, similar to friction.

Air resistance happens when an object moving through air collides with air molecules. The collisions of the air molecules with the moving object "pushes back against the moving object" in the direction opposite that the object moves. The result is that air resistance acts against the direction of motion. It slows the acceleration of falling objects by pushing back in the up direction—up is opposite of down in this case.

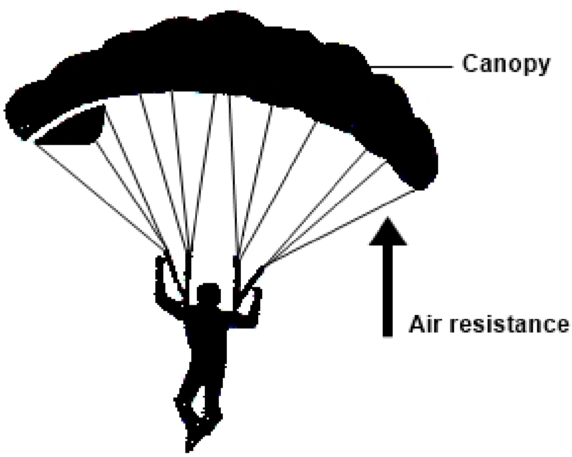
Illustrative Example 2

The jumper is in a state of freefall through air. Air resistance force happens when the jumper's body collides with air molecules. The air molecules "push back" on his body in the up direction. Up is the direction opposite of his fall. This reduces his acceleration as he falls because the air resistance force is against his downward force by gravity.

Air resistance also happens to laterally moving vehicles. The truck is moving to the east and passing through Earth's atmosphere. Gas molecules in the air flow around the truck, but some collide with the front end of the truck, pushing back to the west, the direction opposite of the truck's motion.



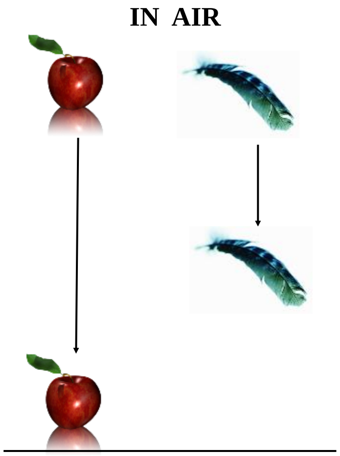
The airplane passes through Earth's atmosphere and the air within. Air streams flow around the body of the airplane, but some air collides with the nosecone, airplane body, and wings. The shape of aircraft is fairly streamlined to minimize air resistance and maximize airflow around the body (i.e., aerodynamics). If the airplane is flying to the south, the force of air resistance is to the north.



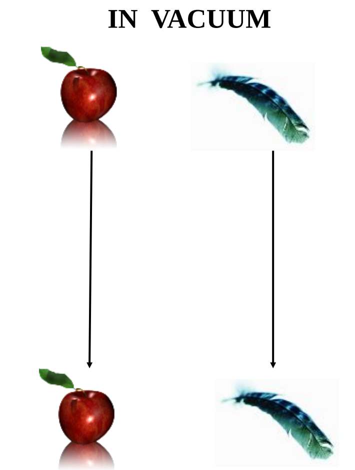
A parachute canopy is very large with a big surface area. That large surface area "catches air" as the jumper and parachute fall. Air under the canopy pushes back with a very large air resistance force on the canopy in the up direction. The large air resistance force allows the parachute to descend at a very slow rate.

Galileo's observations only hold true if and only if the two falling objects are fairly equal in size, shape, and density. His observations are not true for objects that are very dissimilar in their masses and surface areas. Lightweight objects with large surface areas, like feathers and paper, are greatly affected by air resistance and will float and drift downward rather than fall straight down because they catch air molecules and air currents. As a thought experiment, if all air was removed from the room, such as in a vacuum, all objects regardless of surface area and mass would freefall at the same acceleration. No air means no air resistance. No air resistance means that falling objects are only affected by gravity and no other forces that impede the motion of the falling objects.

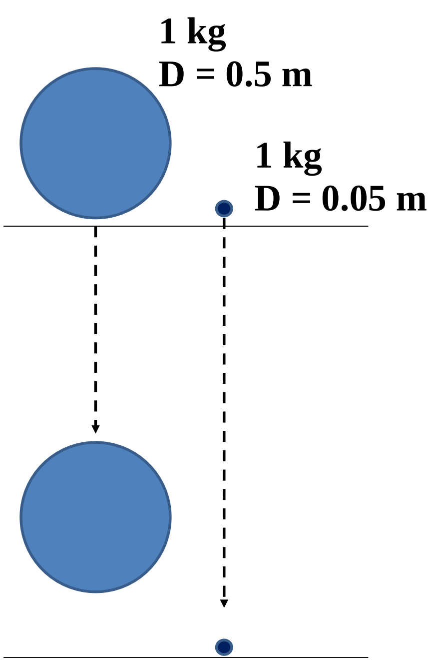
Illustrative Example 3



If an apple and a feather were released from the same height above the floor at the same time in a room **with air** present, the apple would fall faster and hit the ground first. The apple has greater mass and its rounded shape is less affected by air. The feather, in contrast, would flutter and drift slowly to the ground. The feather has a very slender, flat shape with a large surface area. Its density is very low by comparison. Air will interfere with the feather as it falls.



If all air was removed from the room (**a vacuum**) and the same experiment recreated, the apple and the feather would fall with the same acceleration and impact the ground at the same time. Without air, the only force acting upon both the apple and feather is the pull of gravity. As a result, they fall unbiased by air and accelerate at the $-9.81\ m/s^2$ of the Earth's gravity field.



If two objects of similar shape differ greatly by size, the object with the smaller surface area and greater density will accelerate faster and impact the ground first. The larger and least dense will be affected more by air resistance and take longer to fall to the ground.

Two 1-kg balls of very different sizes were dropped from the same height above the ground. The much larger ball has a large surface area that impacts a lot of air molecules as it falls. The smaller ball has a very small surface area that impacts very few air molecules as it falls. The larger ball will experience a greater push back by air resistance as it falls—colliding with more air molecules, more air molecule pushing upward on it.

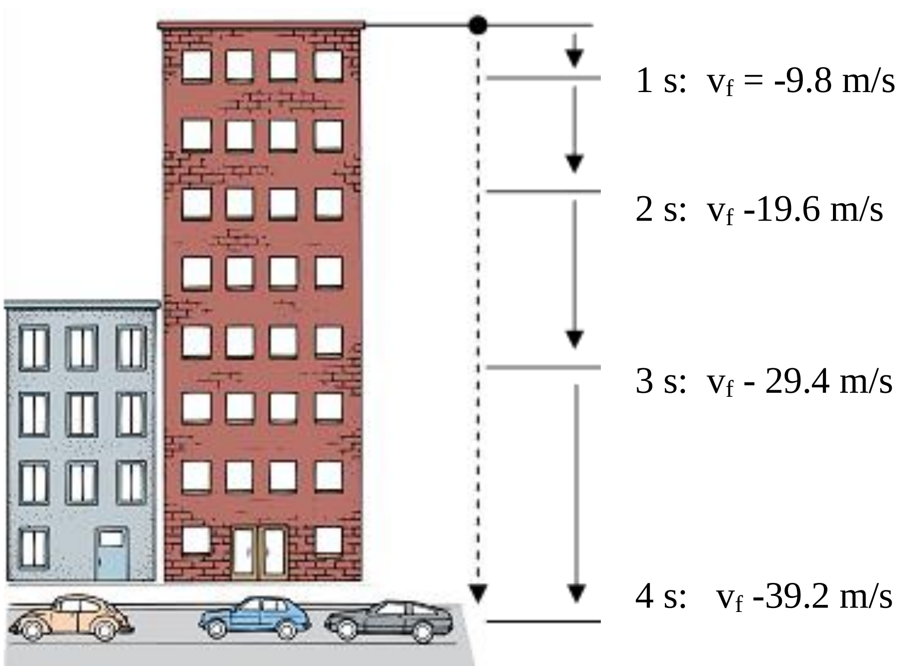
Calculating Vertical Velocity (up or down)

Final velocity (vertical motion)

$$v_f = v_o - g \cdot t$$

v_f = vertical velocity (m/s)
v_0 = initial velocity (m/s)
g = 9.81 m/s^2
t = time (s)

In a past lesson, we used the equation $v_f = v_o + a \cdot t$ to calculate the final velocity of a horizontal moving object that underwent acceleration. The equation used to calculate how fast an object moves up or down is almost identical, $v_f = v_o - g \cdot t$. The variable g in the velocity equation is an acceleration (like *a* in the linear final velocity equation), it is the acceleration in Earth's gravity field. **If the object is moving up, the velocity is positive. If the object is falling down, the velocity is negative.** Assuming that air resistance is negligible, for every second that the object freefalls, the object will accelerate by -9.81 m/s^2. The initial velocity, v_0, would be 0 m/s if the object is released from a stationary position. It would be positive velocity if the object was initially thrown upward. It would be negative velocity if the object was initially thrown downward.



The figure to the left shows how velocity of a freefalling object changes with increasing freefall time. The object was released (v_0 = 0 m/s). The object accelerates because the velocity is getting faster. For every additional second that the object fell, its downward velocity increased by -9.81 m/s because Earth's gravity field is accelerating matter downward at 9.81 m/s^2.

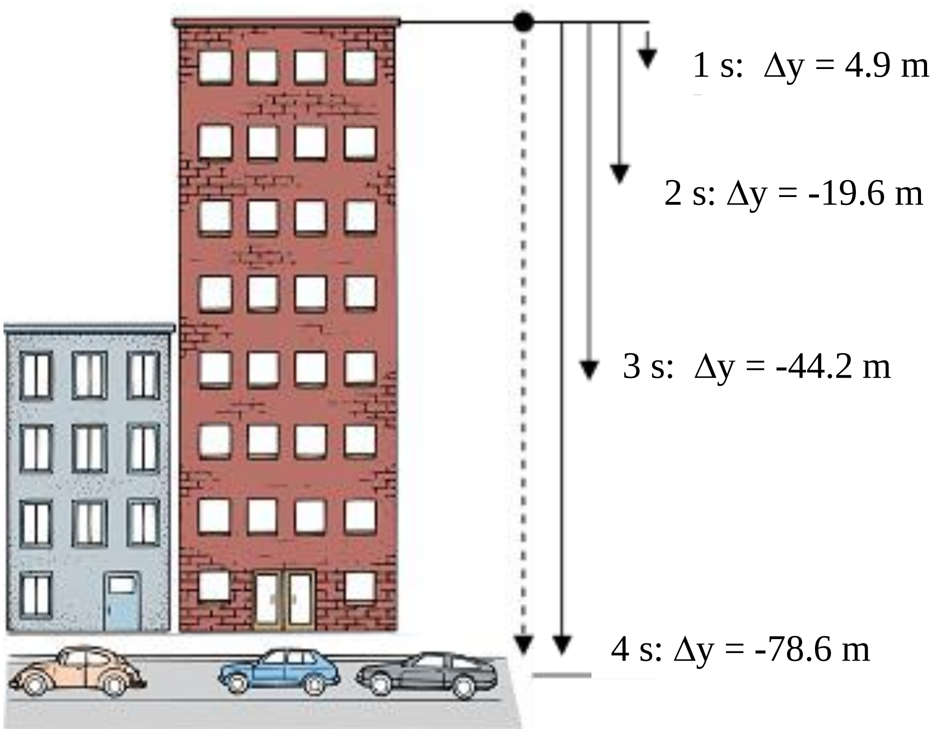
Calculating changes in vertical position (displacement up or down)

Change in vertical position (vertical motion)

$$\Delta y = v_0 \cdot t - \frac{1}{2} g \cdot t^2$$

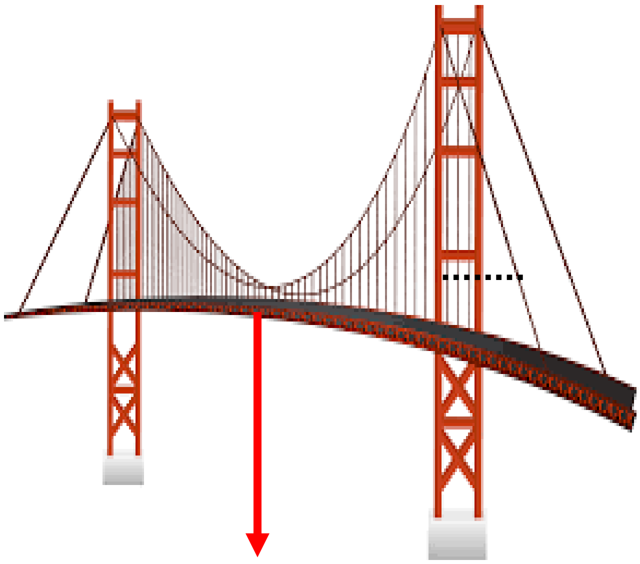
$$y_f = y_0 + v_0 \cdot t - \frac{1}{2} g \cdot t^2$$

y_f = position to which the object fell (m)
y_0 = initial position at release (m)
Δy = vertical displacement (m)
$g = 9.81\ m/s^2$
t = time to fall (s)



If an object only freefalls, the freefall distance is negative because the displacement is downward relative to the point of release. Freefall distance increases geometrically—it becomes progressively becomes greater and greater for each second the object falls because the time variable is squared. The freefall distance is compounded as it falls because the object is falling progressively faster and faster and covering an increasing downward distance every second.

Calculation Example 1
Drop the Object



A boy releases (drops, lets go of) a penny from a bridge that spans a canyon. The penny freefalls for 6.0 seconds before the penny strikes the river at the bottom of the canyon. Air resistance is negligible.

(a) Calculate the freefall velocity of the penny at the instant of impact.

(b) Calculate how far the penny fell.

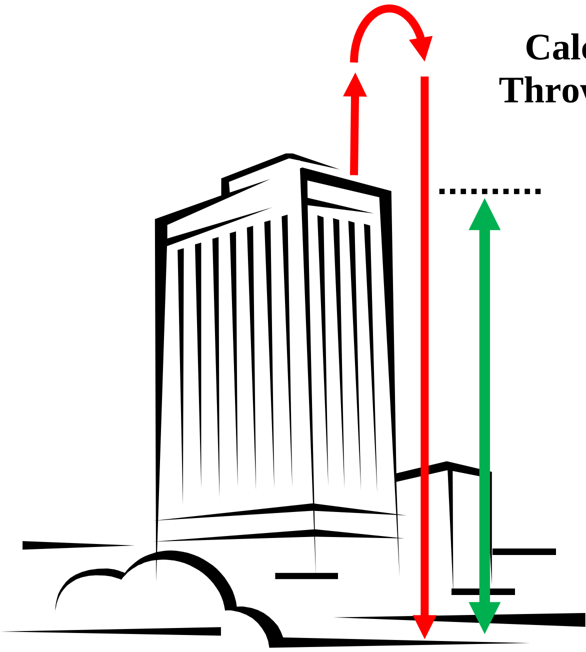
The red arrow shows the path of the penny as it fell from the bridge to the bottom of the canyon.

(a) The freefall velocity of the penny after falling for 6.0 consecutive seconds is -58.8 m/s.

$$v_f = v_0 - g \cdot t$$
$$v_v = 0\,{}^{m}/_{s} - 9.81\,{}^{m}/_{s^2} \cdot 6.0s = -58.8\,{}^{m}/_{s}$$

(b) The vertical displacement is -176.6 m. The height of the bridge deck was 176.6 meters above the river.

$$\Delta y = v_0 \cdot t - \frac{1}{2} g \cdot t^2$$
$$\Delta y = (0\,{}^{m}/_{s} \cdot 6.0s) - \left(\frac{1}{2} \cdot 9.81\,{}^{m}/_{s^2} \cdot (6.0s)^2\right) = -176.6m$$



Calculation Example 2
Throw object up and over

A man is on the roof of a building. He throws a rock straight up into the air with an initial velocity of 5.0 m/s. The rock's time of flight is 7.2 seconds before it hits the sidewalk below.

(a) Calculate the freefall velocity of the rock at the instant of impact.

(b) Calculate the height of the building.

The red arrows show the path taken by the rock from the instant it was thrown to its impact on the sidewalk below. The green arrow shows the vertical displacement (Δy) of the rock as calculated in the 2nd equation.

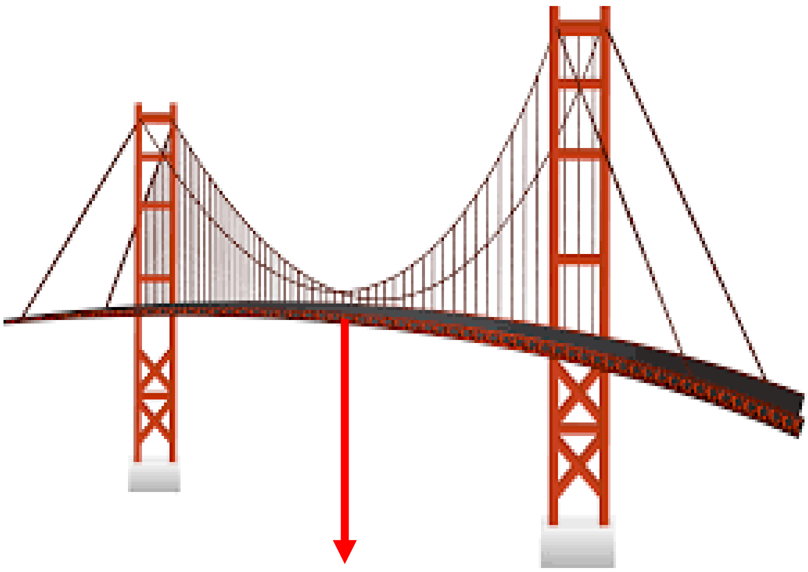
(a) The freefall velocity of the rock when it impacts the ground is -65.6 m/s.

$$v_f = v_0 - g \cdot t$$
$$v_v = 5.0\, {}^{m}/_{s} - 9.81\, {}^{m}/_{s^2} \cdot 7.2s = -65.6\, {}^{m}/_{s}$$

(b) The height of the building is 218.0 m above the sidewalk. The rock fell a total displacement of -218.0 m.

$$\Delta y = v_0 \cdot t - \frac{1}{2} g \cdot t^2$$
$$\Delta y = (5.0\, {}^{m}/_{s} \cdot 7.2s) - \left(\frac{1}{2} \cdot 9.81\, {}^{m}/_{s^2} \cdot (7.2s)^2\right)$$
$$= -218.0m$$

Calculation Example 3
Object is thrown down



A boy throws a penny straight down with an initial velocity of -8.0 m/s from a bridge that spans a canyon. The penny's time of flight before it impacts the ground below is 7.9 seconds.

(a) Calculate the freefall velocity of the penny at the instant of impact.
(b) Calculate the height of the bridge above the canyon floor.

The red arrow shows the path of the penny after it was thrown down and fell from the bridge to the bottom of the canyon.

(a) The freefall velocity of the penny when it impacted the canyon floor was -85.4 m/s.

$$v_f = v_0 - g \cdot t$$
$$v_f = -8.0\,{}^{m}/_{s} - 9.81\,{}^{m}/_{s^2} \cdot 7.9s = -85.4\,{}^{m}/_{s}$$

(b) The freefall distance of the penny after falling for 7.9 consecutive seconds is -369 m. The height of the bridge deck was 369 meters above the canyon floor.

$$\Delta y = v_0 \cdot t - \frac{1}{2} g \cdot t^2$$
$$\Delta y = (-8.0\,{}^{m}/_{s} \cdot 7.9s) - \left(\frac{1}{2} \cdot 9.81\,{}^{m}/_{s^2} \cdot (7.9s)^2\right) = -369m$$