Physics I course – Winter 2022

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Learning outcomes

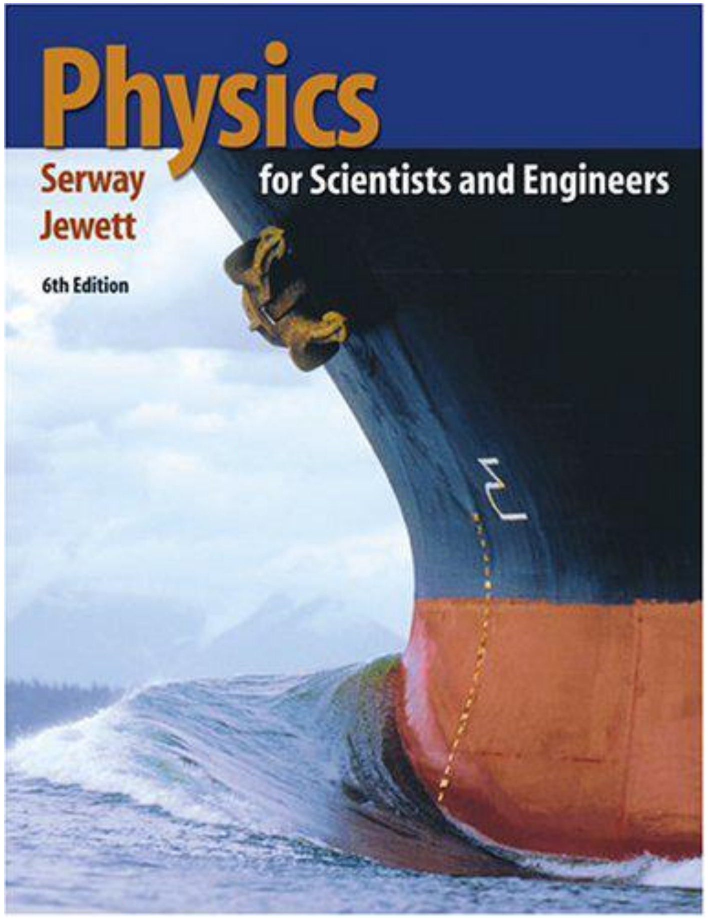
Objective:

The major objectives of this course are for students to learn the fundamental principles of classical mechanics, to develop solid and systematic problem solving skills, and to lay the foundations for further studies in physics, physical sciences, and engineering.

Topics:

1. Physics and measurement
2. Motion in one dimension
3. Vectors
4. Motion in two dimensions
5. The laws of motion
6. Energy and energy transfer
7. Potential energy
8. Linear momentum and collisions
9. Rotation of a rigid object about a fixed axis
10. Angular momentum
11. Static equilibrium and elasticity
12. Fluid mechanics
13. Introduction to oscillatory motion

References


Physics
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for Scientists and Engineers

Chapter 2: Motion in One Dimension (Sections 2.5-2.7)

Learning outcomes

i. Learn where the kinematics equations of motion came to be

ii. Describe the motion of feely falling objects

iii. Problem solving strategy

Kinematic Equations

The kinematic equations can be used with any particle under uniform acceleration.

The kinematic equations may be used to solve any problem involving one-dimensional motion with a constant acceleration.

You may need to use two of the equations to solve one problem.

Many times there is more than one way to solve a problem.

Kinematic Equations, 1

For constant a_x,

$$v_{xf} = v_{xi} + a_x t$$

Can determine an object's velocity at any time t when we know its initial velocity and its acceleration

- Assumes $t_i = 0$ and $t_f = t$

Does not give any information about displacement

Kinematic Equations, 2

For constant acceleration,

$$v_{x,avg} = \frac{v_{xi} + v_{xf}}{2}$$

The average velocity can be expressed as the arithmetic mean of the initial and final velocities.

- This applies only in situations where the acceleration is constant.

Kinematic Equations, 3

For constant acceleration,

$$x_f = x_i + v_{x,avg}\, t = x_i + \frac{1}{2}\left(v_{xi} + v_{fx}\right)t$$

This gives you the position of the particle in terms of time and velocities.

Doesn’t give you the acceleration

Kinematic Equations, 4

For constant acceleration,

$$x_f = x_i + v_{xi} t + \frac{1}{2} a_x t^2$$

Gives final position in terms of velocity and acceleration

Doesn't tell you about final velocity

Kinematic Equations, 5

For constant *a*,

$$v_{xf}^2 = v_{xi}^2 + 2a_x\left(x_f - x_i\right)$$

Gives final velocity in terms of acceleration and displacement

Does not give any information about the time

When $a = 0$

When the acceleration is zero,

- $v_{xf} = v_{xi} = v_x$
- $x_f = x_i + v_x t$

The constant acceleration model reduces to the constant velocity model.

Kinematic Equations – summary

TABLE 2.2 *Kinematic Equations for Motion of a Particle Under Constant Acceleration*

Equation Number	Equation	Information Given by Equation
2.13	$v_{xf} = v_{xi} + a_x t$	Velocity as a function of time
2.15	$x_f = x_i + \frac{1}{2}(v_{xi} + v_{xf})t$	Position as a function of velocity and time
2.16	$x_f = x_i + v_{xi}t + \frac{1}{2}a_x t^2$	Position as a function of time
2.17	$v_{xf}^2 = v_{xi}^2 + 2a_x(x_f - x_i)$	Velocity as a function of position

Note: Motion is along the *x* axis.

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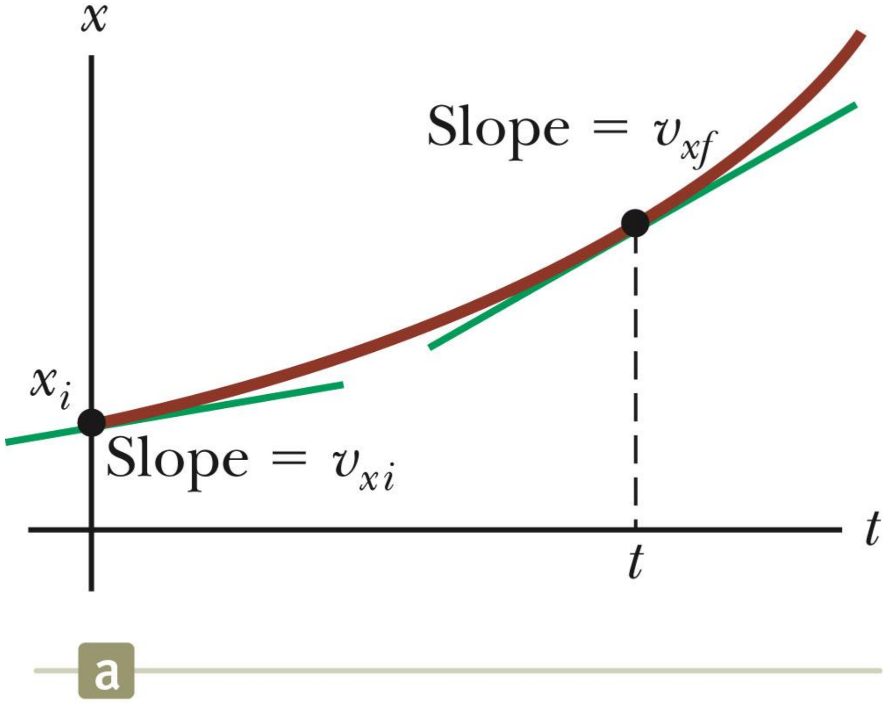
Graphical Look at Motion: Displacement – Time curve

The slope of the curve is the velocity.

The curved line indicates the velocity is changing.

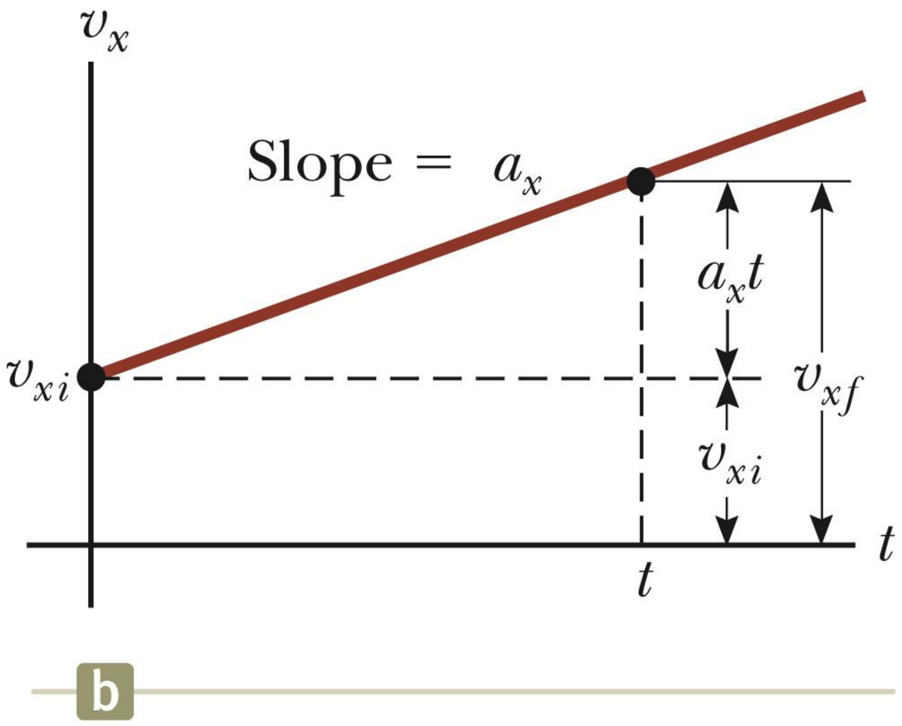
- Therefore, there is an acceleration.



Graphical Look at Motion: Velocity – Time curve

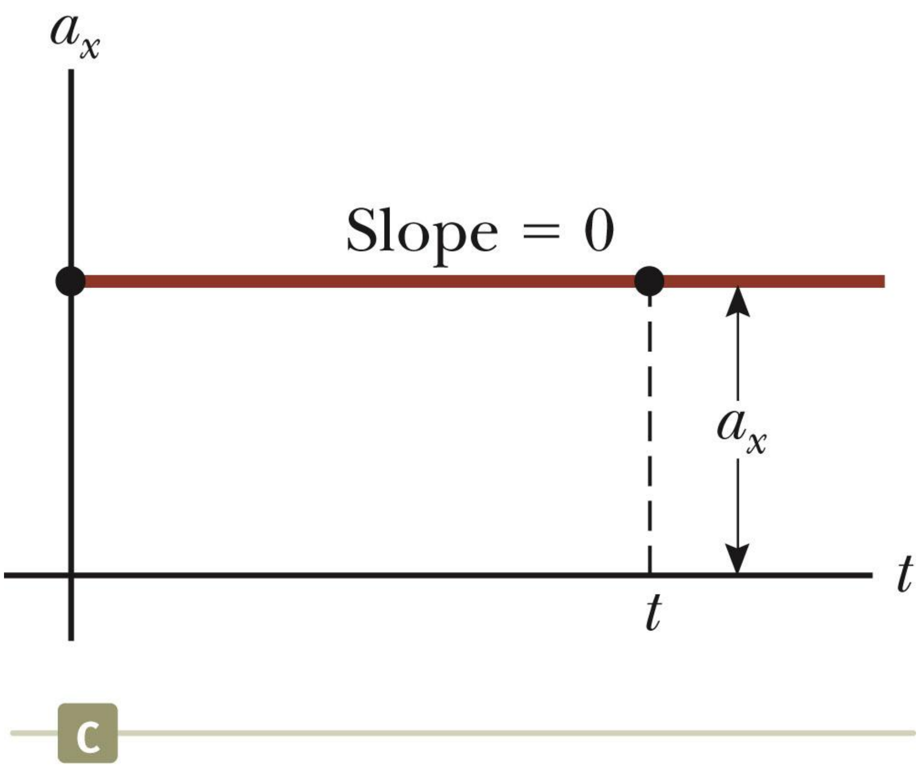
The slope gives the acceleration.

The straight line indicates a constant acceleration.

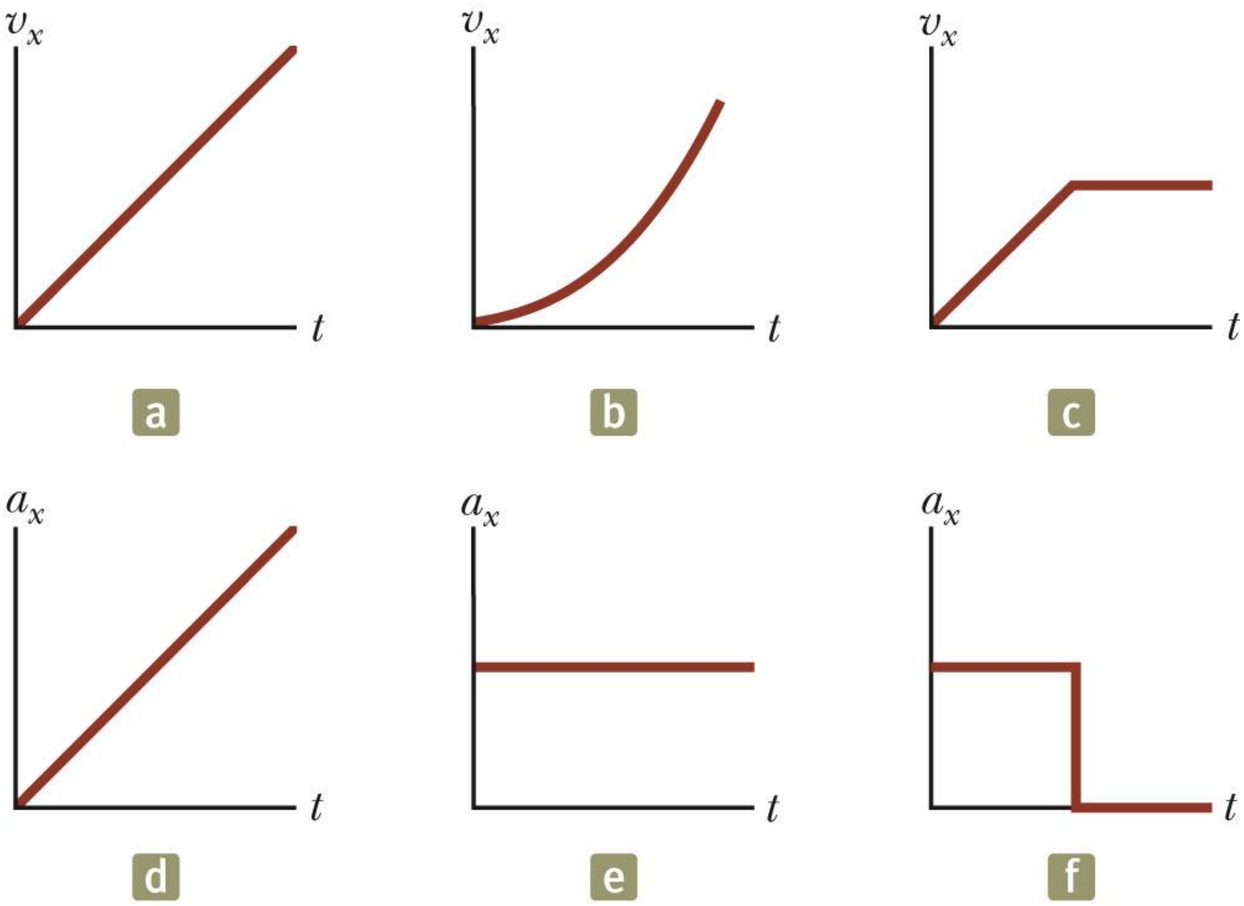


Graphical Look at Motion: Acceleration – Time curve

The zero slope indicates a constant acceleration.



Match the v_x-t graphs with their respective a_x-t graphs



Example

- A police car waits in hiding slightly off the highway.
- A speeding car is spotted by the police car doing a constant 40 m/s.
- At the instant the speeding car passes the police car, the police car accelerates from rest at $4 m/s^2$ to catch the speeding car.
- How long does it take the police car to catch the speeding car?

Example – Solution

Equation for the speeding car: This car has a constant velocity, which is the average velocity, and is not accelerating, so use the equation for displacement with $x_0 = 0$: $x = x_0 + \bar{v}t = \bar{v}t$; Equation for the police car: This car is accelerating, so use the equation for displacement with $x_0 = 0$ and $v_0 = 0$, since the police car starts from rest: $x = x_0 + v_0 t + \frac{1}{2}at^2 = \frac{1}{2}at^2$; Now we have an equation of motion for each car with a common parameter, which can be eliminated to find the solution. In this case, we solve for t . Step 1, eliminating x : $x = \bar{v}t = \frac{1}{2}at^2$; Step 2, solving for t : $t = \frac{2\bar{v}}{a}$. The speeding car has a constant velocity of 40 m/s, which is its average velocity. The acceleration of the police car is 4 m/s^2. Evaluating t, the time for the police car to reach the speeding car, we have $t = \frac{2\bar{v}}{a} = \frac{2(40)}{4} = 20\ \text{s}$.

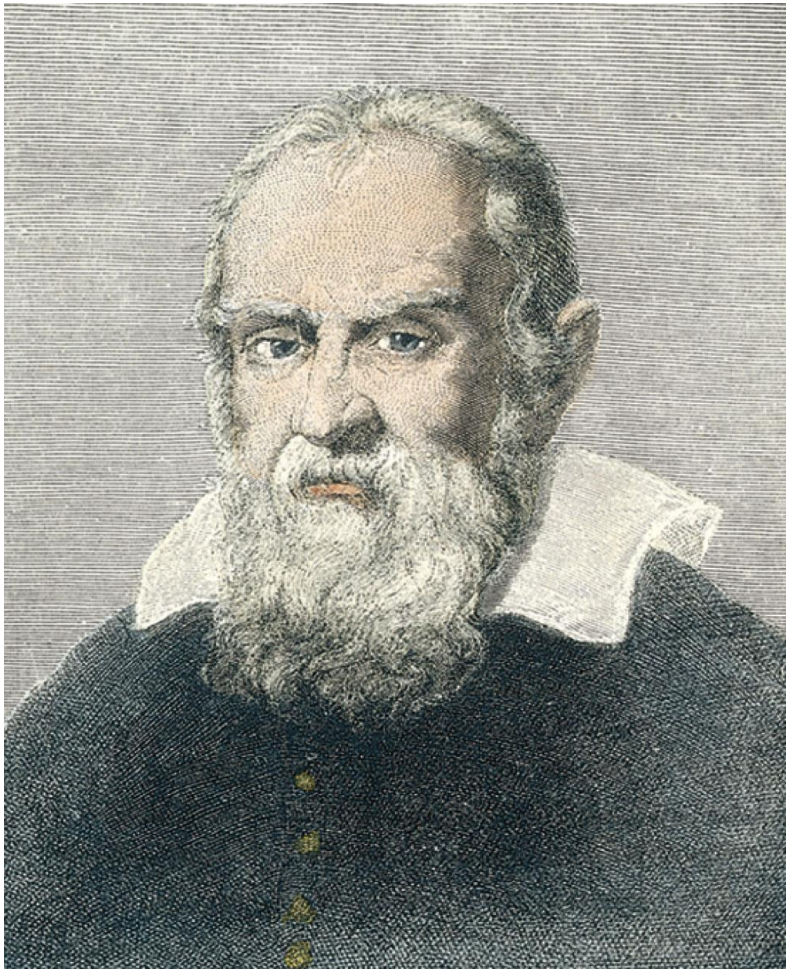
Galileo Galilei

1564 – 1642

Italian physicist and astronomer

Formulated laws of motion for objects in free fall

Supported heliocentric universe



Freely Falling Objects

A ***freely falling object*** is any object moving freely under the influence of gravity alone.

It does not depend upon the initial motion of the object.

- Dropped – released from rest
- Thrown downward
- Thrown upward

Acceleration of Freely Falling Object

The acceleration of an object in free fall is directed downward, regardless of the initial motion.

The magnitude of free fall acceleration is $g = 9.80 \text{ m/s}^2$.

- g decreases with increasing altitude
- g varies with latitude
- 9.80 m/s^2 is the average at the Earth's surface
- The italicized g will be used for the acceleration due to gravity.
  - Not to be confused with g for grams

Acceleration of Free Fall, cont.

We will neglect air resistance.

Free fall motion is constantly accelerated motion in one dimension.

- Use model of a particle under constant acceleration

Let upward be positive

Use the kinematic equations

- With $a_y = -g = -9.80\ \text{m/s}^2$
- Note displacement is in the vertical direction

Free Fall – An Object Dropped

Initial velocity is zero

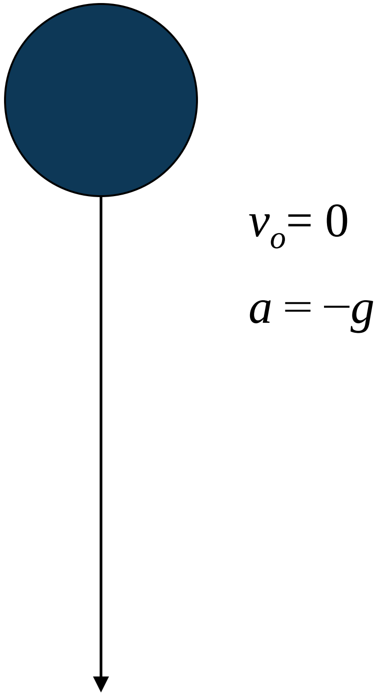
Let up be positive

Use the kinematic equations

- Generally use *y* instead of *x* since vertical

Acceleration is

- $a_y = -g = -9.80 \text{ m/s}^2$

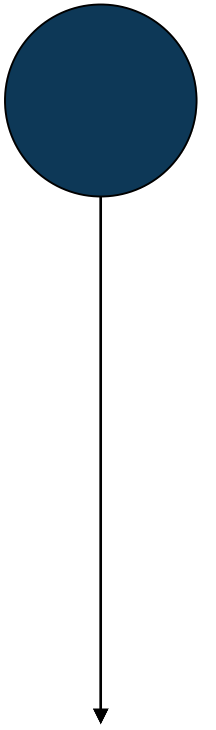


Free Fall – An Object Thrown Downward

$a_y = -g = -9.80 \text{ m/s}^2$

Initial velocity $\neq 0$

- With upward being positive, initial velocity will be negative.

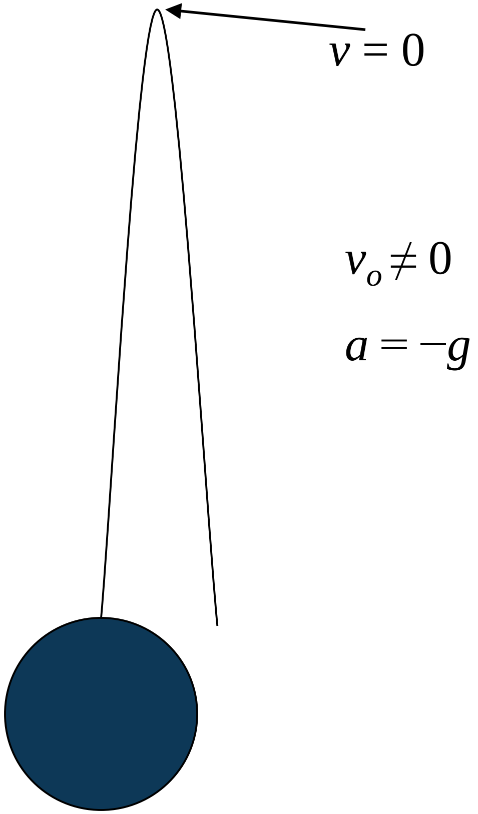


Free Fall – Object Thrown Upward

Initial velocity is upward, so positive

The instantaneous velocity at the maximum height is zero.

$a_y = -g = -9.80 \text{ m/s}^2$ everywhere in the motion



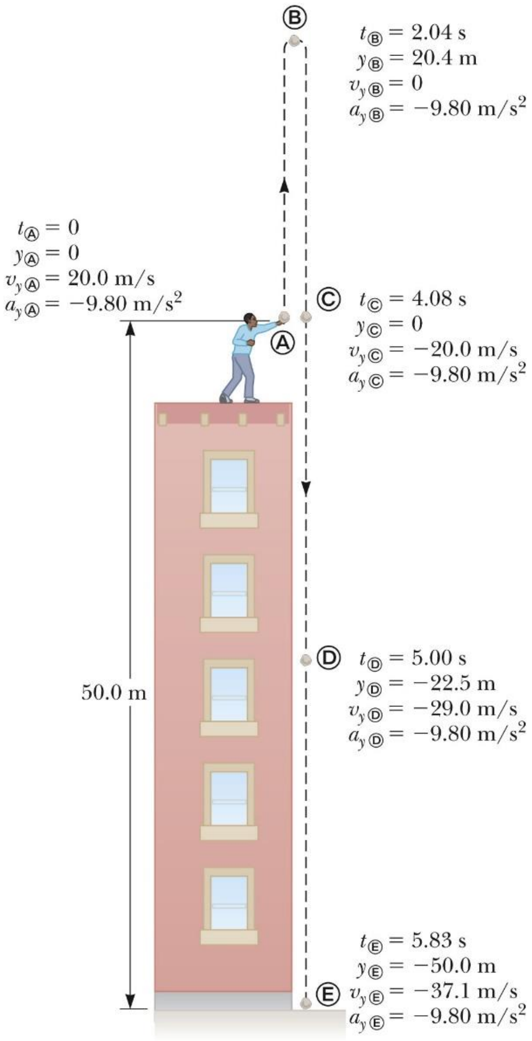
Free Fall Example

Initial velocity at A is upward (+) and acceleration is $-g$ ($-9.8\ m/s^2$).

At B, the velocity is 0 and the acceleration is $-g$ ($-9.8\ m/s^2$).

At C, the velocity has the same magnitude as at A, but is in the opposite direction.

The displacement is −50.0 m (it ends up 50.0 m below its starting point).



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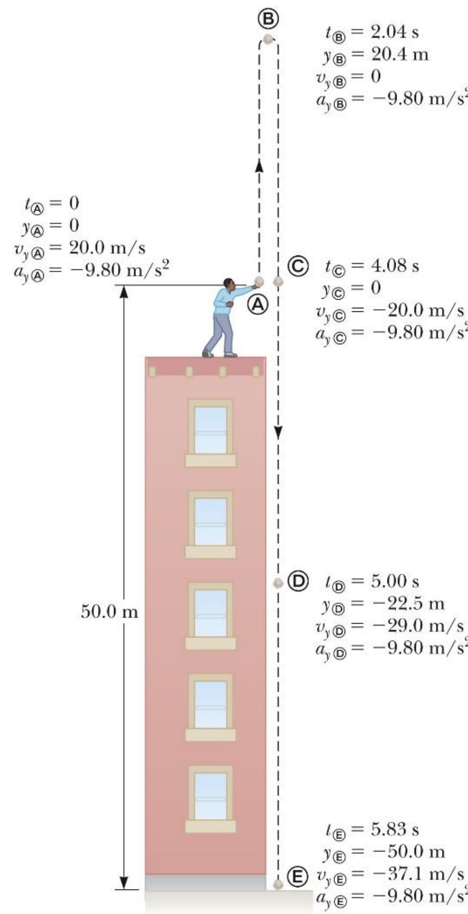
Example

- A stone thrown from the top of a building is given an initial velocity of 20.0 m/s straight upward. The building is 50.0 m high, and the stone just misses the edge of the roof on its way down, as shown in the figure. Using $t_A = 0$ as the time the stone leaves the thrower's hand at position A, determine:

  1. the time at which the stone reaches its maximum height;
  2. the maximum height;
  3. the time at which the stone returns to the height from which it was thrown;
  4. the velocity of the stone at this instant;
  5. the velocity and position of the stone at $t = 5.00$ s.



Example 2.12 Not a Bad Throw for a Rookie! **Interactive**

A stone thrown from the top of a building is given an initial velocity of 20.0 m/s straight upward. The building is 50.0 m high, and the stone just misses the edge of the roof on its way down, as shown in Figure 2.14. Using $t_A = 0$ as the time the stone leaves the thrower's hand at position Ⓐ, determine **(A)** the time at which the stone reaches its maximum height, **(B)** the maximum height, **(C)** the time at which the stone returns to the height from which it was thrown, **(D)** the velocity of the stone at this instant, and **(E)** the velocity and position of the stone at $t = 5.00$ s.

Solution (A) As the stone travels from Ⓐ to Ⓑ, its velocity must change by 20 m/s because it stops at Ⓑ. Because gravity causes vertical velocities to change by about 10 m/s for every second of free fall, it should take the stone about 2 s to go from Ⓐ to Ⓑ in our drawing. To calculate the exact time t_B at which the stone reaches maximum height, we use Equation 2.9, $v_{yB} = v_{yA} + a_y t$, noting that $v_{yB} = 0$ and setting the start of our clock readings at $t_A = 0$:

$$0 = 20.0\ \text{m/s} + (-9.80\ \text{m/s}^2)t$$

$$t = t_B = \frac{20.0\ \text{m/s}}{9.80\ \text{m/s}^2} = \boxed{2.04\ \text{s}}$$

Our estimate was pretty close.

(B) Because the average velocity for this first interval is 10 m/s (the average of 20 m/s and 0 m/s) and because it travels for about 2 s, we expect the stone to travel about 20 m. By substituting our time into Equation 2.12, we can find the maximum height as measured from the position of the thrower, where we set $y_A = 0$:

$$y_{max} = y_B = y_A + v_{xA}t + \tfrac{1}{2}a_y t^2$$

$$y_B = 0 + (20.0\ \text{m/s})(2.04\ \text{s}) + \tfrac{1}{2}(-9.80\ \text{m/s}^2)(2.04\ \text{s})^2$$

$$= \boxed{20.4\ \text{m}}$$

Our free-fall estimates are very accurate.

(C) There is no reason to believe that the stone's motion from Ⓑ to Ⓒ is anything other than the reverse of its motion from Ⓐ to Ⓑ. The motion from Ⓐ to Ⓒ is symmetric. Thus, the time needed for it to go from Ⓐ to Ⓒ should be twice the time needed for it to go from Ⓐ to Ⓑ. When the stone is back at the height from which it was thrown (position Ⓒ), the y coordinate is again zero. Using Equation 2.12, with $y_C = 0$, we obtain

$$y_C = y_A + v_{yA}t + \tfrac{1}{2}a_y t^2$$

$$0 = 0 + 20.0t - 4.90t^2$$

This is a quadratic equation and so has two solutions for $t = t_C$. The equation can be factored to give

$$t(20.0 - 4.90t) = 0$$

One solution is $t = 0$, corresponding to the time the stone starts its motion. The other solution is $\boxed{t = 4.08\ \text{s},}$ which

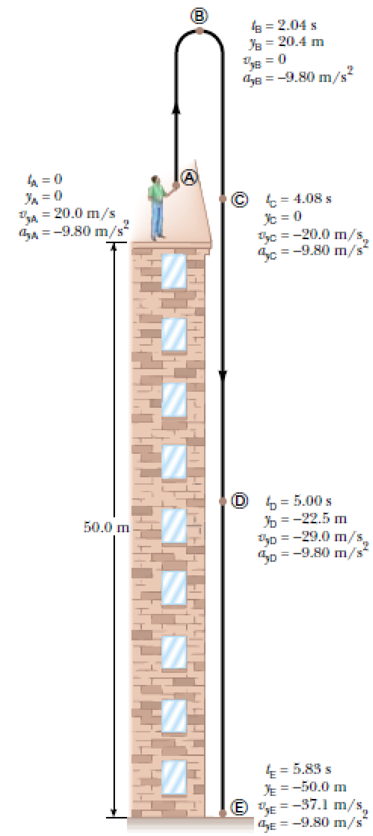


Figure 2.14 (Example 2.12) Position and velocity versus time for a freely falling stone thrown initially upward with a velocity $v_{yi} = 20.0$ m/s.

is the solution we are after. Notice that it is double the value we calculated for t_B.

(D) Again, we expect everything at Ⓒ to be the same as it is at Ⓐ, except that the velocity is now in the opposite direction. The value for t found in (c) can be inserted into Equation 2.9 to give

$$v_{yC} = v_{yA} + a_y t = 20.0\ \text{m/s} + (-9.80\ \text{m/s}^2)(4.08\ \text{s})$$

$$= \boxed{-20.0\ \text{m/s}}$$

The velocity of the stone when it arrives back at its original height is equal in magnitude to its initial velocity but opposite in direction.

(E) For this part we ignore the first part of the motion (Ⓐ→Ⓑ) and consider what happens as the stone falls from position Ⓑ, where it has zero vertical velocity, to position Ⓓ. We define the initial time as $t_B = 0$. Because the given time for this part of the motion relative to our new zero of time is 5.00 s − 2.04 s = 2.96 s, we estimate that the acceleration due to gravity will have changed the speed by about 30 m/s. We can calculate this from Equation 2.9, where we take $t = 2.96$ s:

$$\begin{aligned} v_{yD} &= v_{yB} + a_y t = 0\text{ m/s} + (-9.80\text{ m/s}^2)(2.96\text{ s}) \\ &= \boxed{-29.0\text{ m/s}} \end{aligned}$$

We could just as easily have made our calculation between positions Ⓐ (where we return to our original initial time $t_A = 0$) and Ⓓ:

$$\begin{aligned} v_{yD} &= v_{yA} + a_y t = 20.0\text{ m/s} + (-9.80\text{ m/s}^2)(5.00\text{ s}) \\ &= -29.0\text{ m/s} \end{aligned}$$

To further demonstrate that we can choose different initial instants of time, let us use Equation 2.12 to find the position of the stone at $t_D = 5.00$ s (with respect to $t_A = 0$) by defining a new initial instant, $t_C = 0$:

$$\begin{aligned} y_D &= y_C + v_{yC}t + \tfrac{1}{2}a_y t^2 \\ &= 0 + (-20.0\text{ m/s})(5.00\text{ s} - 4.08\text{ s}) \\ &\quad + \tfrac{1}{2}(-9.80\text{ m/s}^2)(5.00\text{ s} - 4.08\text{ s})^2 \\ &= \boxed{-22.5\text{ m}} \end{aligned}$$

What If? What if the building were 30.0 m tall instead of 50.0 m tall? Which answers in parts (A) to (E) would change?

Answer None of the answers would change. All of the motion takes place in the air, and the stone does not interact with the ground during the first 5.00 s. (Notice that even for a 30.0-m tall building, the stone is above the ground at $t = 5.00$ s.) Thus, the height of the building is not an issue. Mathematically, if we look back over our calculations, we see that we never entered the height of the building into any equation.

General Problem Solving Strategy

In addition to basic physics concepts, a valuable skill is the ability to solve complicated problems.

Steps in a general problem solving approach:

- Conceptualize
- Categorize
- Analyze
- Finalize

Problem Solving – Conceptualize

Think about and understand the situation.

Make a quick drawing of the situation.

Gather the numerical information.

- Include algebraic meanings of phrases.

Focus on the expected result.

- Think about units.

Think about what a reasonable answer should be.

Problem Solving – Categorize

Simplify the problem.

- Can you ignore air resistance?
- Model objects as particles

Classify the type of problem.

- Substitution
- Analysis

Try to identify similar problems you have already solved.

- What analysis model would be useful?

Problem Solving – Analyze

Select the relevant equation(s) to apply.

Solve for the unknown variable.

Substitute appropriate numbers.

Calculate the results.

- Include units

Round the result to the appropriate number of significant figures.

Problem Solving – Finalize

Check your result.

- Does it have the correct units?
- Does it agree with your conceptualized ideas?

Look at limiting situations to be sure the results are reasonable.

Compare the result with those of similar problems.

Problem Solving – Some Final Ideas

When solving complex problems, you may need to identify sub-problems and apply the problem-solving strategy to each sub-part.

These steps can be a guide for solving problems in this course.

Exercises

- A helicopter descends from a height of 600 m with uniform acceleration, reaching the ground at rest in 5.00 minutes. Determine the acceleration of the helicopter and its initial velocity.

- A falcon dives at a pigeon. The falcon starts with zero downward velocity and falls with the acceleration of gravity. If the pigeon is 76.0 m below the initial height of the falcon, how long does it take the falcon to intercept the pigeon?

Any questions?