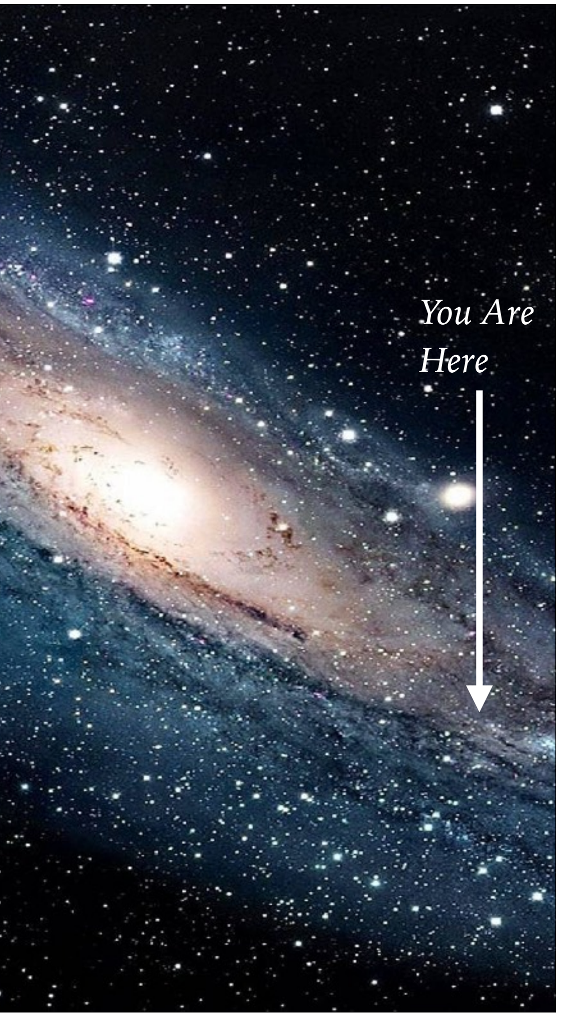
BOOK II: FORCES & MOTION

Where You Are, Where You're Going,
And How You're Getting There

CHAPTER 1: WHERE ARE YOU?

Describing the Essentials of Position, Velocity, Acceleration, & Time



CHAPTER 1: WHERE ARE YOU?

- If you were to write a description of your location to be as specific as possible, it might go something along the lines of:

  4463 Oak Grove Dr, Rm.323
  La Cañada, CA 91011, United States of America
  Earth, Solar System, Milky Way
  Local Group, Virgo Supercluster, Universe

- But who wouldn't be able to find you based on your description?

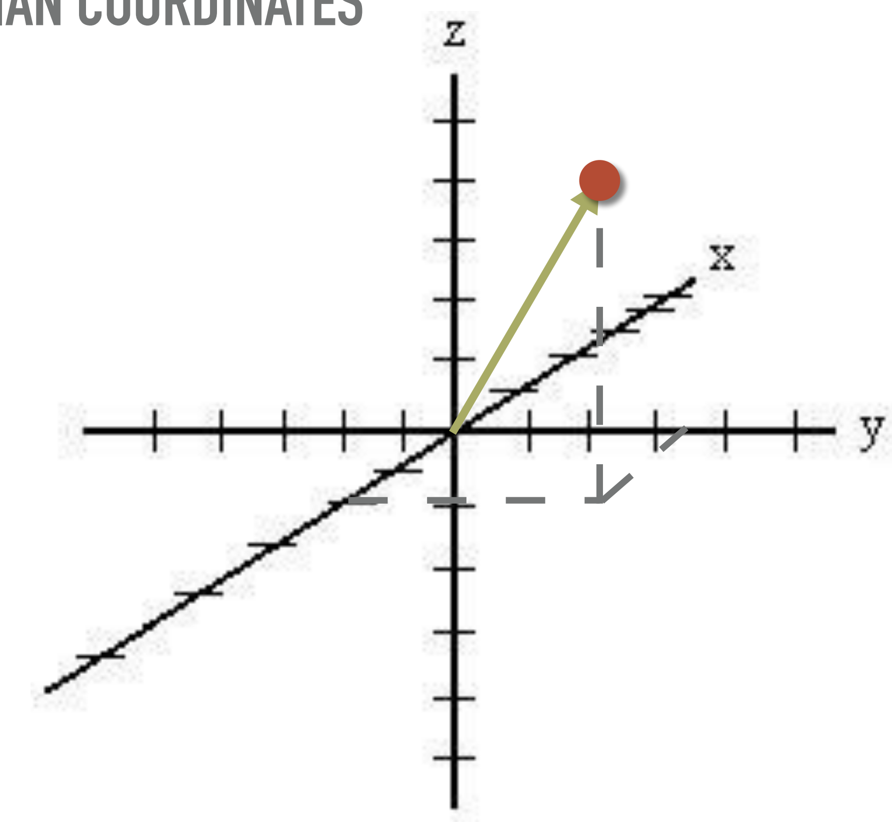
We want a system for describing position that is as simple and unambiguous as possible.

(Convenient)

3 WAYS TO DESCRIBE WHERE YOU ARE:

(and where you're going)

CARTESIAN COORDINATES



All coordinate systems start by picking a reference point to act as the origin and an orientation to decide what direction the axes of the coordinate system point.

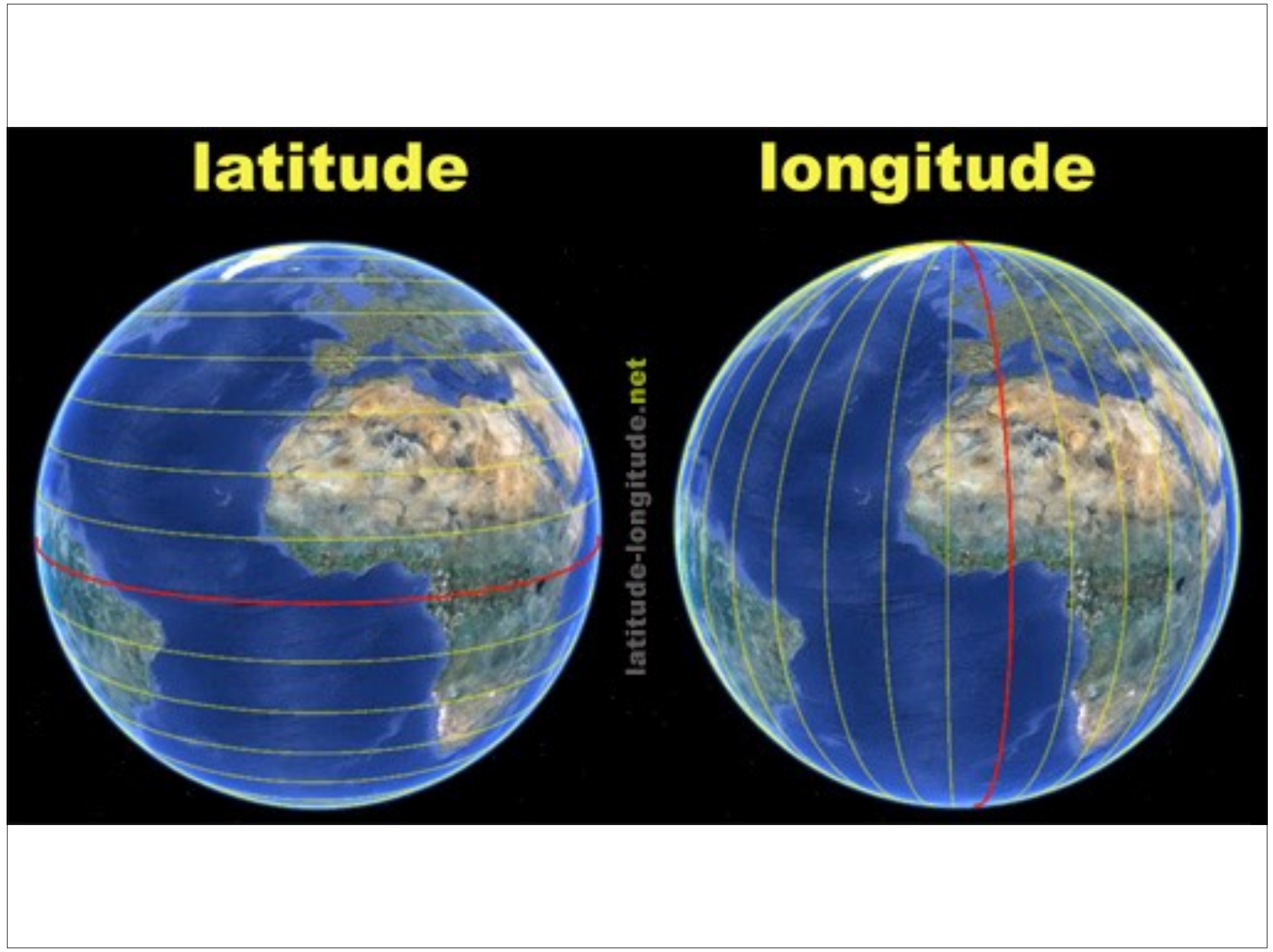
Cartesian coordinates, also called rectangular coordinates, describe position using the axes x-, y-, & z-. All three represent distances, but in different directions. For instance,

x: how far forward or backward

y: how far left or right

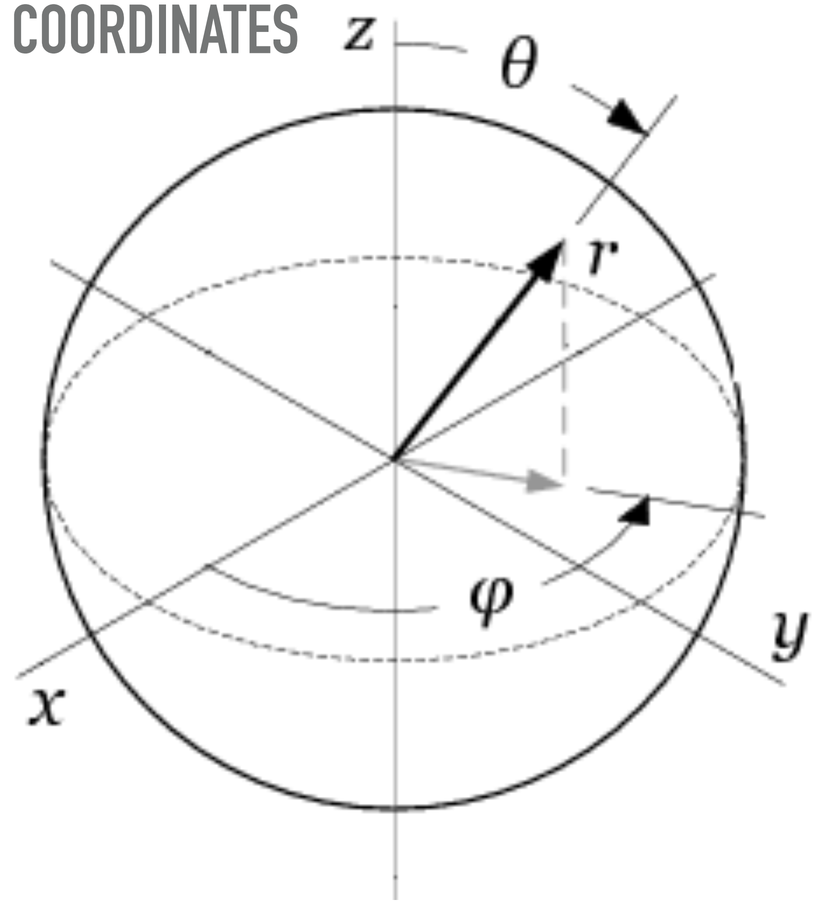
z: how far up or down

Describe the position of the vase on the table. Using cartesian coordinates and starting from the corner of the room, you might say the vase is about 6 ft in the x-direction, 8 ft in the y-direction, and 2 ft in the z-direction and assign it the position (6, 8, 2).



When we want to describe a location on the surface of the Earth, we often describe it using latitude and longitude. On Earth, latitude is a coordinate that tells you how far north or south of the equator (drawn in red) that location is, and longitude tells you how far east or west of the prime meridian (also drawn in red). With those two coordinates plus elevation, you can locate anything on, above, or below the surface of the Earth.

SPHERICAL COORDINATES



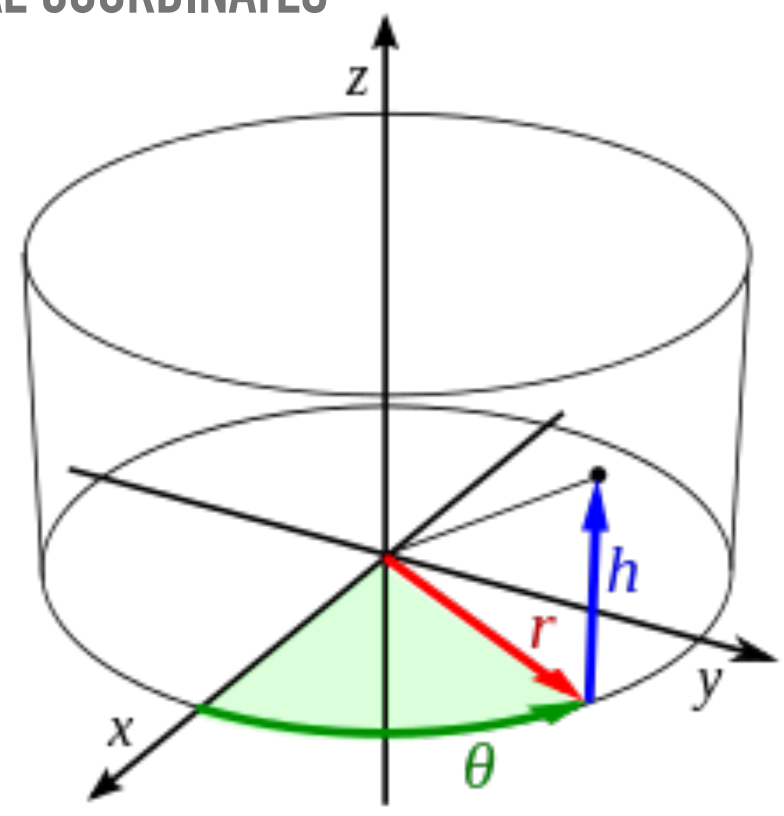
The coordinate system that uses latitude, longitude, and elevation to describe a location is called *spherical coordinates*. Spherical coordinates use the variables r, θ (theta), and ϕ (phi). In this case, r represents a distance while θ and ϕ represent angles.

r: how far from the center of the sphere (e.g. radius of the Earth plus elevation)

θ: latitude

ϕ: longitude

CYLINDRICAL COORDINATES

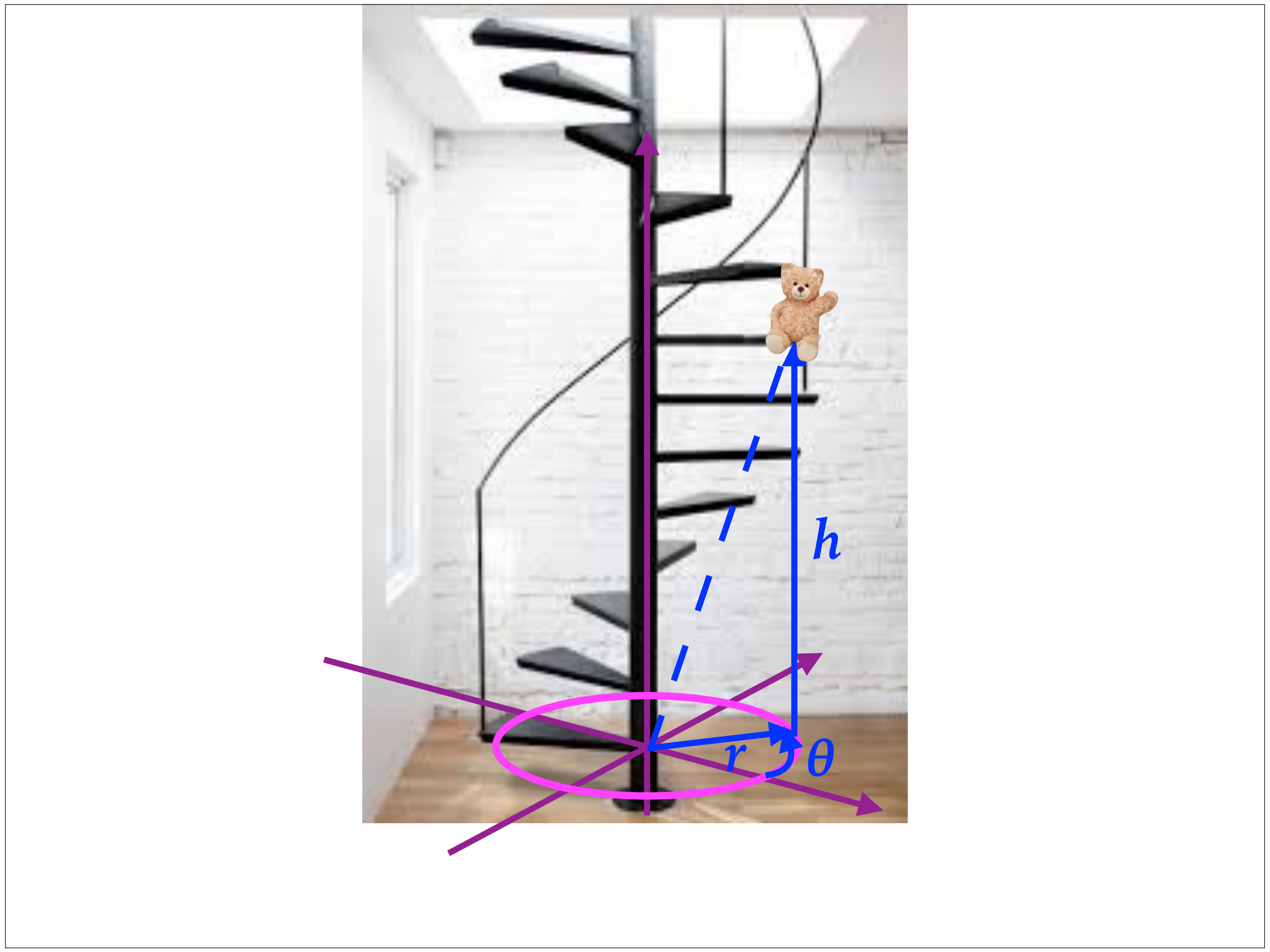


Lastly, *cylindrical coordinates* describe location using two distances and one angle.

r: distance from the central axis of the cylinder

h: distance along the cylinder, parallel to the central axis

θ: angle relative to the reference direction



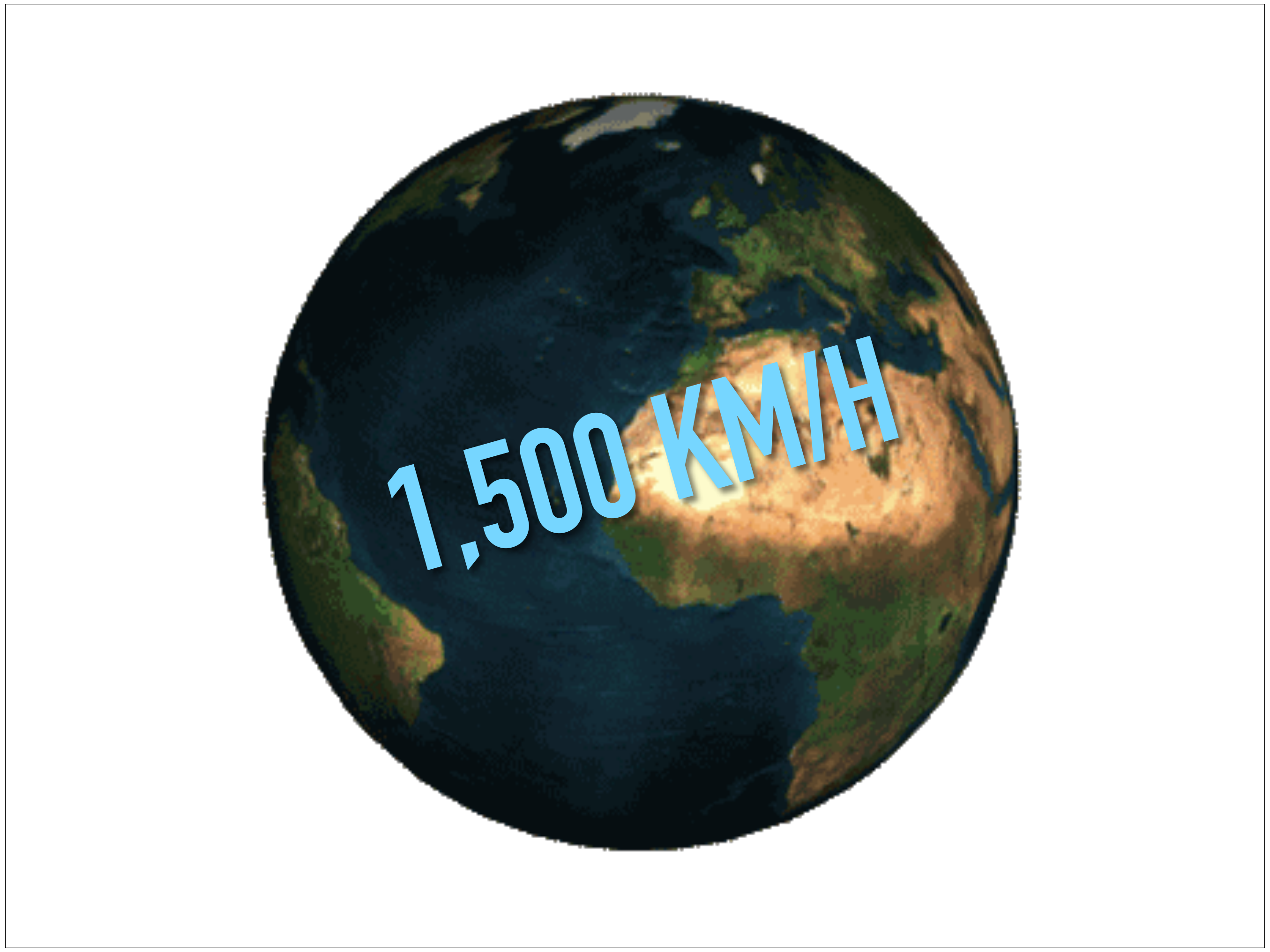
In cylindrical coordinates, r describes how far the teddy bear is sitting from the central pole; h tells you how high above the ground he is; and θ gives the angle of the position relative to the first step

SCENE I: WHERE ARE YOU?

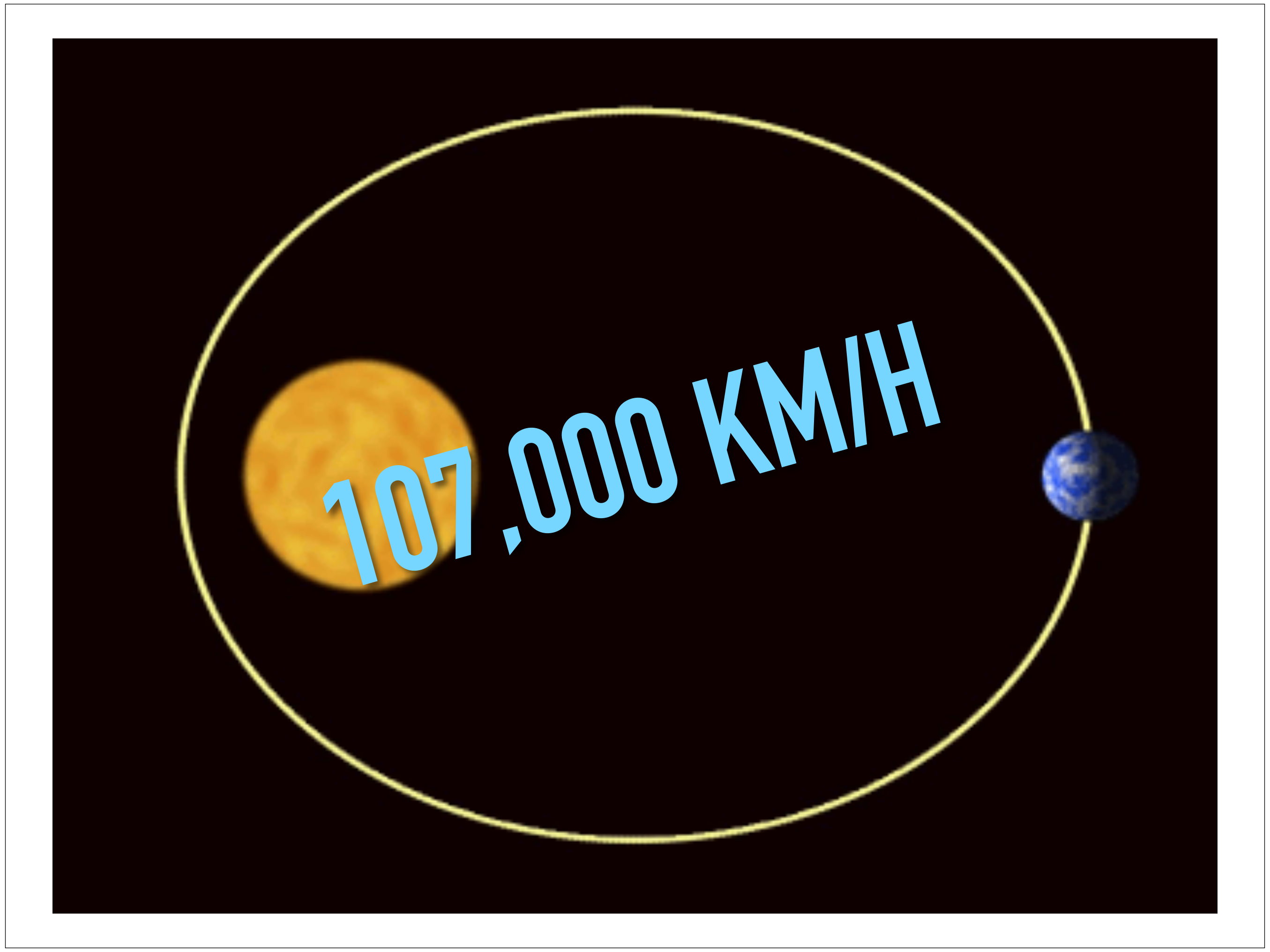
- Describe the position of…
  1. Yourself
  2. Disneyland
  3. Shanghai
  4. Mars
- Pick a convenient reference point for the origin and the orientation of your axes
- Which coordinate system makes the most sense?

DON'T MOVE!

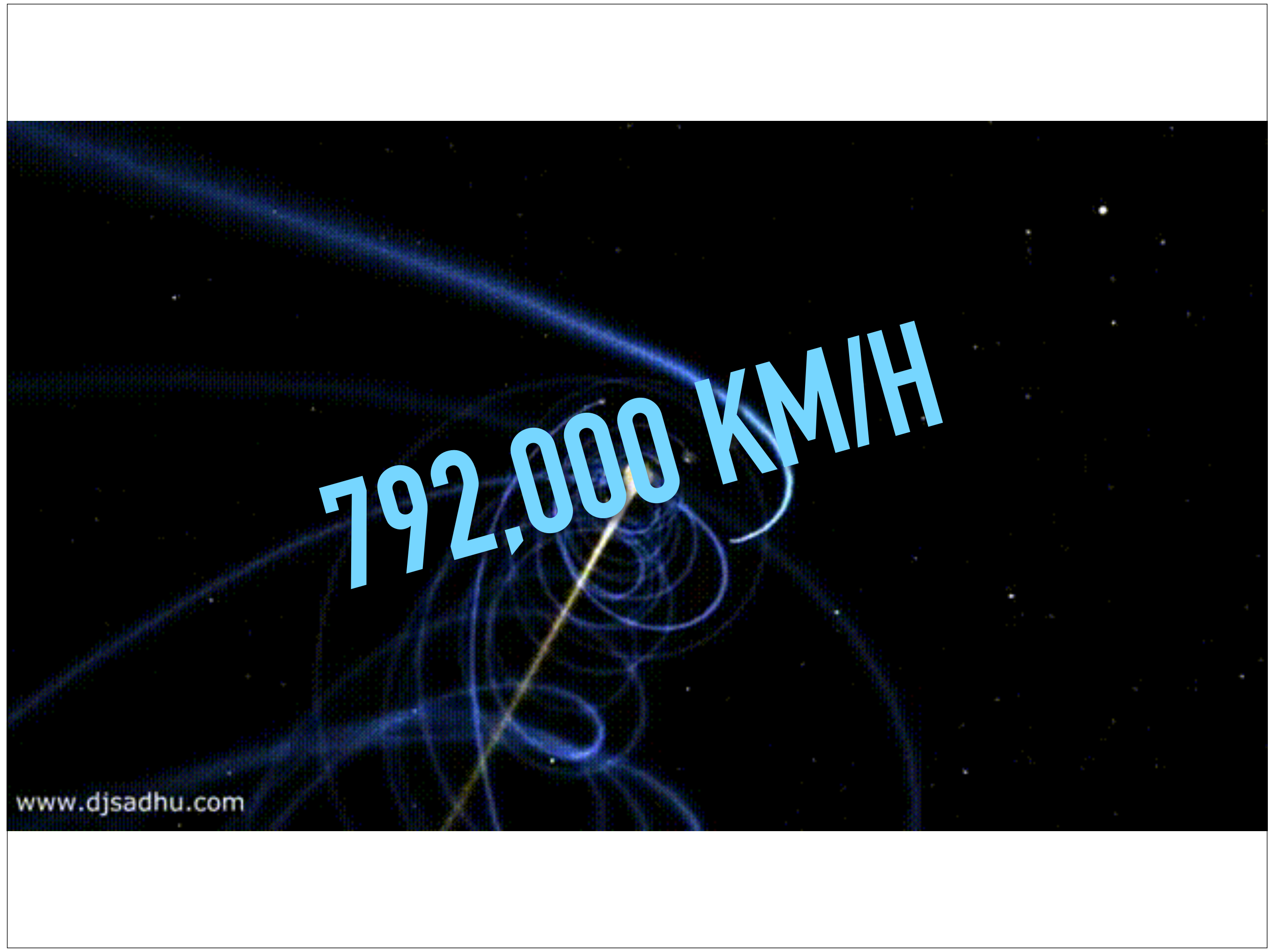
You're not moving, right?



The Earth rotates about its axis at 1,500 km/h



The Earth also revolves around the Sun at 107,000 km/h



The Solar System orbits around the galaxy at 792,000 km/h

And the Universe is expanding, causing just about every galaxy to speed away from each other at roughly 2.1 million km/h

> Life is in infinite motion; at the same time it is motionless.
>
> *-Debasish Mridha*

Whenever we talk about location or motion, it is always relative to something else. When we say a car is moving at 60 mph, it’s implied to mean 60 mph relative to the road, because it’s certainly not moving at 60 mph relative to the passenger inside or the other car driving next to it.

Frame of reference — a framework that is used in physics for observation and mathematical description usually consisting of an observer, a coordinate system, and a clock assigning times at positions with respect to the coordinate system.

Loosely, a frame of reference is the perspective, or point of view, from which you are making comparisons and doing calculations

> In physics, a negative sign indicates direction

Once you've established your reference frame, things above you might be considered to have a positive position while things below you be considered to have a negative position, or things moving to the right might be considered to have a positive velocity while things moving to the left would be considered to have a negative velocity. Which is considered positive and which is negative is doesn't really matter — the point is to describe the oppositeness of directions like above vs. below or right vs. left — as long as you're consistent.

SCENE I: WHERE ARE YOU?

- *Vector* — a quantity with both magnitude and direction
- *Scalar* — a quantity with magnitude only, no direction

Examples of vector quantities include displacement, velocity, acceleration, force, momentum, impulse, etc.

Examples of scalar quantities include distance, mass, energy, power, charge, size, etc. In physics, speed is the scalar version of velocity that doesn’t include direction.

MOTION GRAPHS

- *Speed* — the rate at which an object moves
- *Velocity* — the speed and direction of a moving object
- *Acceleration* — the rate at which speed or direction changes

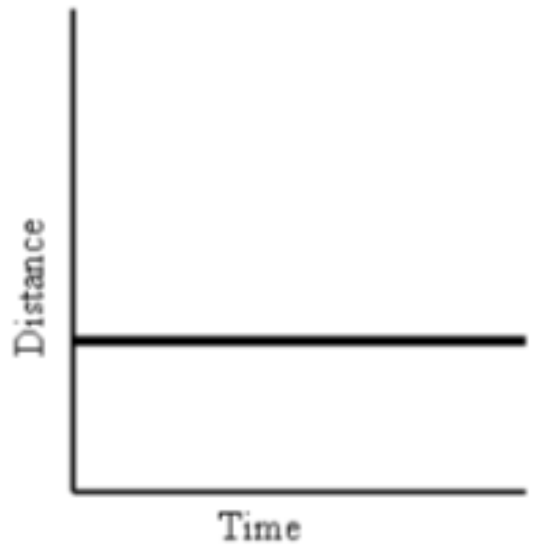
Describing the motion of an object is occasionally hard to do with words. Sometimes graphs help make motion easier to picture, and therefore understand.

DISTANCE VS. TIME GRAPHS

- Time is always plotted on the x-axis (bottom of the graph). The further to the right on the axis, the longer the time from the start.
- Distance is plotted on the y-axis (side of the graph). The higher up the graph, the further from the start.

Plotting distance against time can tell you a lot about motion.

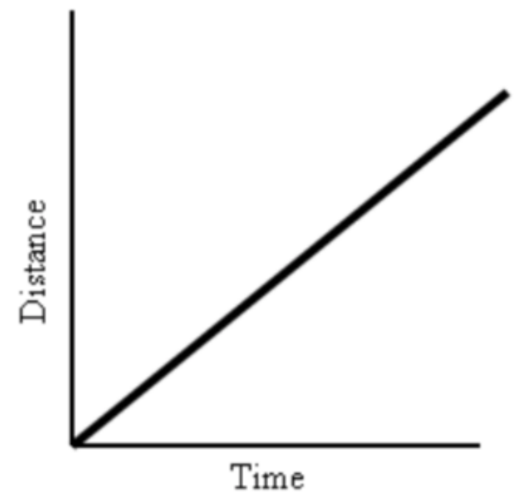
DISTANCE VS. TIME GRAPHS



- Time is increasing to the right, but its distance does not change. It is not moving. We say it is **At Rest**.

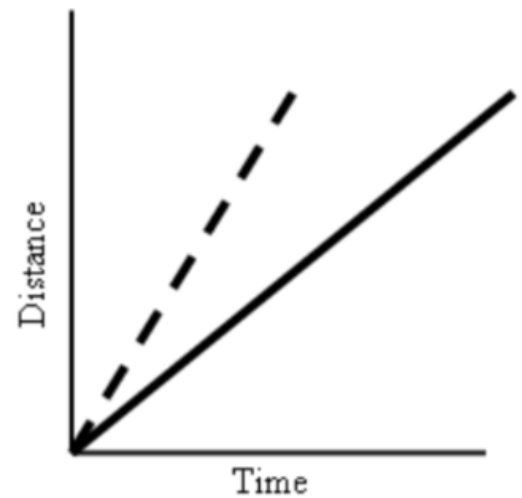
If an object is not moving, a horizontal line is shown on a distance-time graph.

DISTANCE VS. TIME GRAPHS



- Time is increasing to the right, and distance is increasing constantly with time. The object moves at a **constant speed**.
- **Constant speed** is shown by **straight lines** on a graph.

If an object is moving at a constant speed, it means it has the same increase in distance in a given time

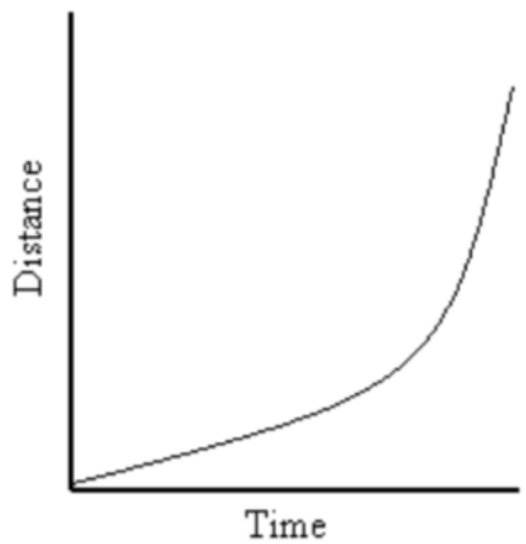


DISTANCE VS. TIME GRAPHS

- A steeper line indicates a larger distance moved in a given time. In other words, **higher speed**.
- Both **lines are straight**, so both **speeds are constant**.

Let’s look at two moving objects:
Both of the lines in the graph show that each object moved the same distance, but the steeper dashed line got there before the other one

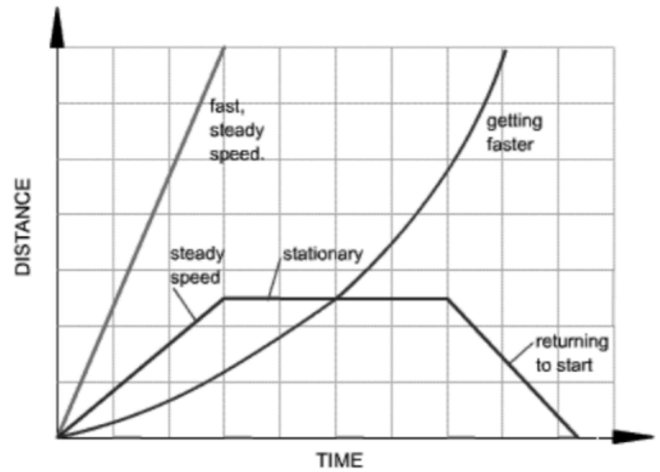
DISTANCE VS. TIME GRAPHS



- The line on this graph is curving upwards. This shows an **increase in speed**, since the line is getting steeper:
- In other words, in a given time, the distance the object moves is change (getting larger). It is **accelerating**.

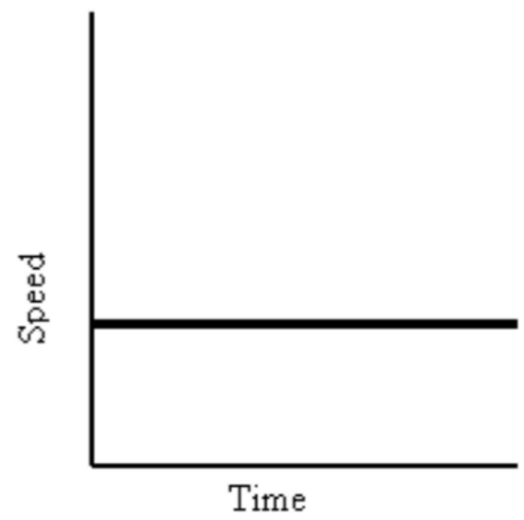
Graphs that show acceleration look different from those that show constant speed.

DISTANCE VS. TIME GRAPHS



- The steeper the graph, the faster the motion.
- A horizontal line means the object is not changing its position - it is not moving, it is at rest.
- A downward sloping line means the object is returning to the start.

A distance-time graph tells us how far an object has moved with time.

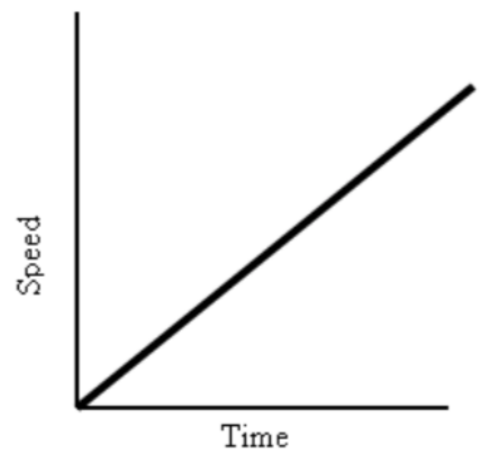


SPEED VS. TIME GRAPHS

- Speed-Time graphs look much like Distance-Time graphs. Be sure to read the labels! Time is plotted on the x-axis. Speed or velocity is plotted on the x-axis.
- A **straight horizontal line** on a speed-time graph means that **speed is constant**. It is not changing over time.
- **A straight line does not mean that the object is not moving!**

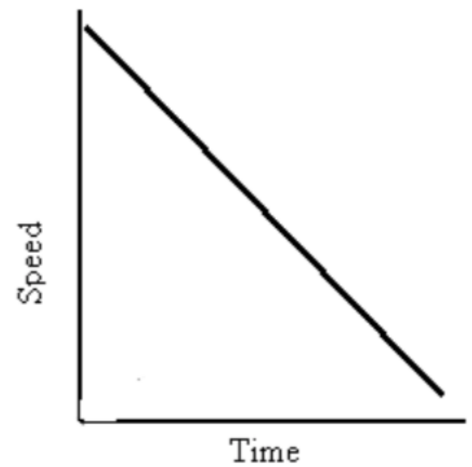
Speed-Time graphs are also called Velocity-Time graphs.

SPEED VS. TIME GRAPHS



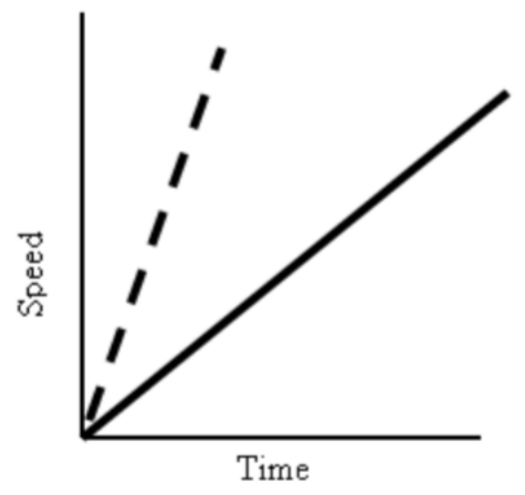
- This graph shows **increasing speed**. The moving object is **accelerating**.

SPEED VS. TIME GRAPHS



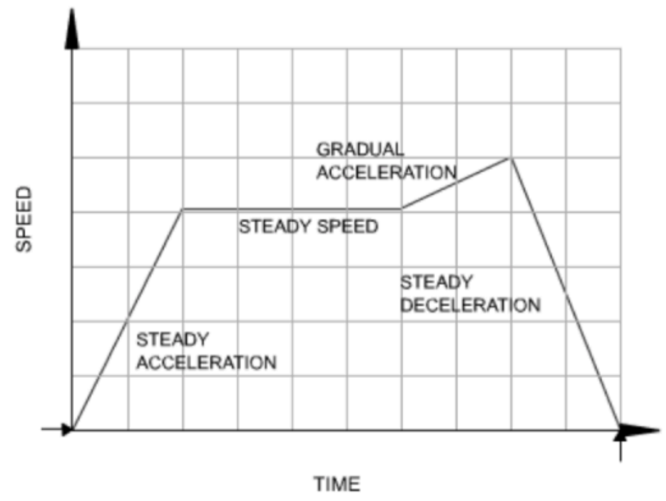
- This graph shows **decreasing speed**. The moving object is **decelerating**.

SPEED VS. TIME GRAPHS



- Both the dashed and solid line show increasing speed.
- Both lines reach the same top speed, but the solid one takes longer.
- The dashed line shows a **greater acceleration**.

SPEED VS. TIME GRAPHS

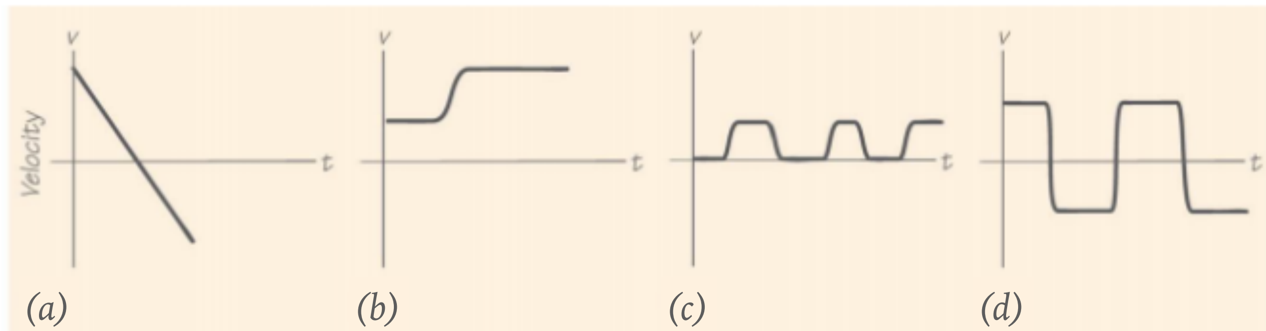


- The steeper the graph, the greater the acceleration.
- A horizontal line means the object is moving at a constant speed.
- A downward sloping line means the object is slowing down.

A speed - time graph shows us how the speed of a moving object changes with time.

Velocity Graphs – Match the motion

1. An idealized ping-pong match
2. Baton being passed in a relay race
3. A tennis ball thrown vertically upward
4. Driving along a road with badly synchronized red lights



- Answers: 1) d, 2) b, 3) a, 4) c

INSTANTANEOUS VELOCITY

- You are in a car heading downtown, as you can see from the speedometer your speed is 40 mph.
- Knowing downtown is 10 miles away, how long should it take you?

A little *distance* = *rate* x *time* might lead you to believe the drive should only take 15 minutes

IS THAT TRUE?

But of course if you've ever made the drive from La Cañada to DTLA, you know it takes more than 15 minutes. DTLA really is 10 miles away, and a car is very likely to make it to speeds of 40 mph at some point during the drive, but the car is also likely to do a lot of speeding up and slowing down along the way. Our estimate failed to take traffic into consideration!

- *Instantaneous* velocity (v) is what the speedometer on your car tells you.
- *Average* velocity (v_{avg}) is what GPS uses to calculate your estimated time of arrival

$$\Delta x = v_{avg}\, \Delta t$$

This equation is the better, more accurate version of *distance* = *rate* x *time*

"Δ" means "change," so Δx = change in position = $x_{final} - x_{initial}$

SANITY CHECK

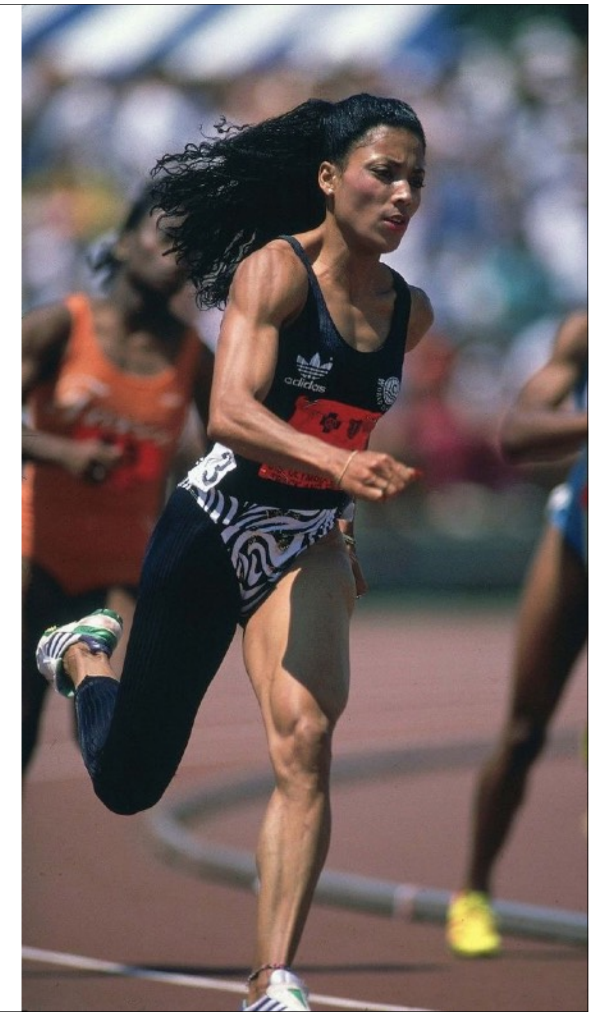
- If the instantaneous acceleration is zero, does it mean that the instantaneous velocity is zero?
- If the instantaneous velocity of an object is zero, does it mean that the instantaneous acceleration is zero?

Not necessarily! Zero acceleration just means the velocity isn't changing, so as long as an object is moving at a constant speed, it can have zero acceleration and non-zero velocity.

An object can also have zero velocity and non-zero acceleration. For example, when you throw an object up in the air, gravity is always accelerating that object toward the ground at 9.8 m/s^2. This results in the object moving slower and slower as it moves upwards before it changes direction and starts moving faster and faster downwards. At the very top of its arc, at the instant it switches from moving upward to moving downward, the object's velocity is zero.

CHAPTER 2: WHERE ARE YOU GOING?

Kinematics — The Study of How Things Move



Florence Griffith-Joyner, USA, World Record Women’s 200m at 21.34 s. So how fast can she run, exactly?

KINEMATIC EQUATIONS

1. $v_f = v_i + a\Delta t$

2. $x_f = x_i + v_i\Delta t + \frac{1}{2} a\Delta t^2$

3. $v_f^2 = v_i^2 + 2a\Delta x$

The three kinematic equations describe the relationship between:

1. *position* (*x*) in meters (m)
2. *velocity* (*v*) in meters per second (m/s)
3. *acceleration* (*a*) in meters per second per second (m/s^2)
4. and *time* (*t*) in seconds (s)

Important note: these equations are only valid under *constant* acceleration

EXAMPLE 1

Sonic, the world's fastest hedgehog™, is escaping from the city. In 3.00 s, Sonic moves from being 135 m away from the city to 1,165 m away. What is Sonic's average velocity?

ANSWER 1

Givens (w/ SI units)	Applicable Equation	Plug & Chug	
$\Delta t = 3.00\ s$ $x_i = 135\ m$ $x_f = 1165\ m$	$\Delta x = v_{avg} \Delta t$	$v_{avg} = \frac{(1165\ m) - (135\ m)}{(3.00\ s)}$	
	Solve Equation for Unknown		
Unknown	$v_{avg} = \frac{x_f - x_i}{\Delta t}$		
$v_{avg} = ?$		**Answer**	$v_{avg} = 343\ m/s$

Problem Solving Steps:

1. Check that all units are in SI
2. Write down the given info (typically, look for the numbers the question provides)
3. Identify the unknown (what the problem is asking you to solve for)
4. Identify the applicable equation (the equation that includes the unknown and the given info)
5. Rearrange the equation to get the unknown by itself on the left side of the equal sign
6. Plug the given info into the rearranged equation and solve
7. Make sure the final answer includes the correct units

EXAMPLE 2

Brian O'Connor is driving at 54 m/s before deciding he is driving way too fast and a little too furiously. He slows the car to a reasonable 35 m/s in 5.0 s. What is O'Connor's average acceleration?

ANSWER 2

Givens (w/ SI units)	Applicable Equation	Plug & Chug
$v_i = 54\ m/s$ $v_f = 35\ m/s$ $\Delta t = 5.0\ s$	$v_f = v_i + a\,\Delta t$	$a = \frac{(35\ m/s) - (54\ m/s)}{(5.0\ s)}$
Unknown	**Solve Equation for Unknown**	
$a = ?$	$a = \frac{v_f - v_i}{\Delta t}$	**Answer**: $a = -3.8\ m/s^2$

Notice that the acceleration came out negative. In this case, a negative acceleration implies the car is slowing down.

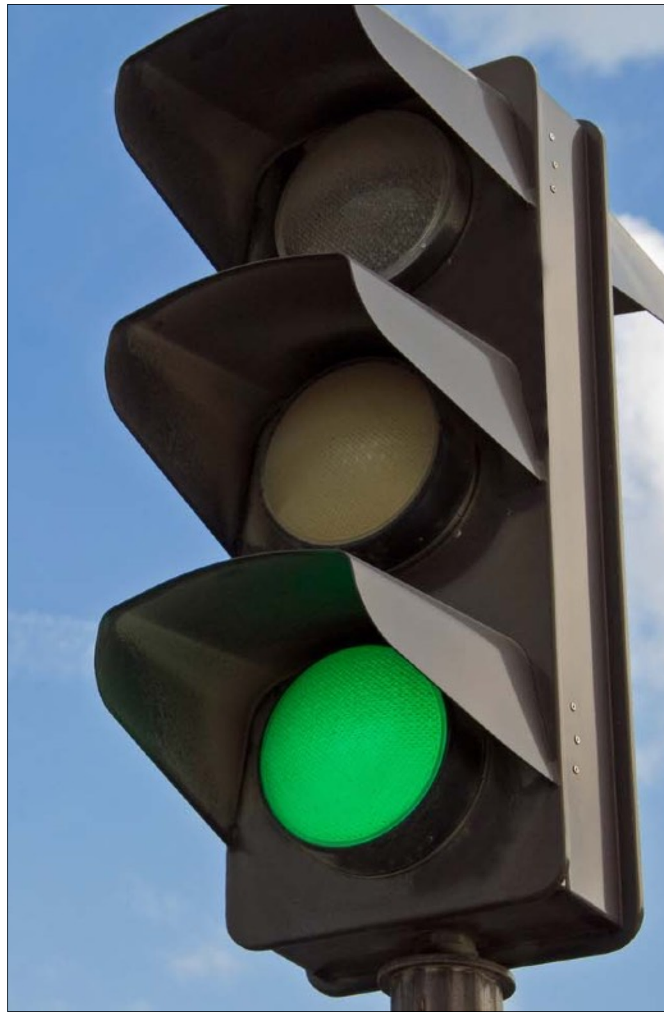
EXAMPLE 3

You are designing an airport for small planes. One kind of airplane that might use this airfield must reach a speed before takeoff of at least 30.0 m/s and can accelerate at 2.00 m/s^2. At least how long should the runway be so this plane can speed to take off?

ANSWER 3

Givens (w/ SI units)	Applicable Equation	Plug & Chug
$v_f = 30.0\ m/s$ $a = 2.00\ s$ $v_i = 0\ m/s$	$v_f^2 = v_i^2 + 2\,a\,\Delta x$	$\Delta x = \dfrac{(30.0\ m/s)^2 - (0\ m/s)^2}{2(2.00\ s)}$
Unknown	**Solve Equation for Unknown**	
$\Delta x = ?$	$\Delta x = \dfrac{v_f^2 - v_i^2}{2\,a}$	**Answer**: $\Delta x = 193\ m$

While the problem doesn't state it explicitly, we know the plane has to start from rest before taking off, meaning v_i = 0 m/s.



EXAMPLE 4

A car initially stopped at a red light then sees the light turn green and accelerates at a constant rate. If it takes the car 5.0 sec to cross the 30.-m-wide intersection, what is the car's rate of acceleration?

ANSWER 4

<table>
<tr><th>Givens (w/ SI units)</th><th>Applicable Equation</th><th colspan="2">Plug & Chug</th></tr>
<tr><td rowspan="2">$v_i = 0 \text{ m/s}$
$\Delta t = 5.0 \text{ s}$
$\Delta x = 30. \text{ m}$</td><td>$\Delta x = v_i \Delta t + \frac{1}{2} a \Delta t^2$</td><td colspan="2" rowspan="3">$a = \frac{(30. \text{ m}) - (0 \text{ m/s})(5.0 \text{ s})}{\frac{1}{2}(5.0 \text{ s})^2}$</td></tr>
<tr><td>Solve Equation for Unknown</td></tr>
<tr><td>Unknown</td><td rowspan="2">$a = \frac{\Delta x - v_i \Delta t}{\frac{1}{2} \Delta t^2}$</td></tr>
<tr><td>$a = ?$</td><td>Answer</td><td>$a = 2.4 \text{ m/s}^2$</td></tr>
</table>

EXAMPLE 5

How high can a human throw something?

- Let's assume a reasonable throwing speed is around 30 m/s (~70 mph) if you're throwing something like a baseball
- As soon as the object leaves your hand, it will start accelerating towards the ground at 9.8 m/s^2 (regardless of what you throw)

Because the acceleration due to gravity is the same for anything falling near the surface of Earth, we often give that acceleration its own variable and say $g = 9.8\ m/s^2$

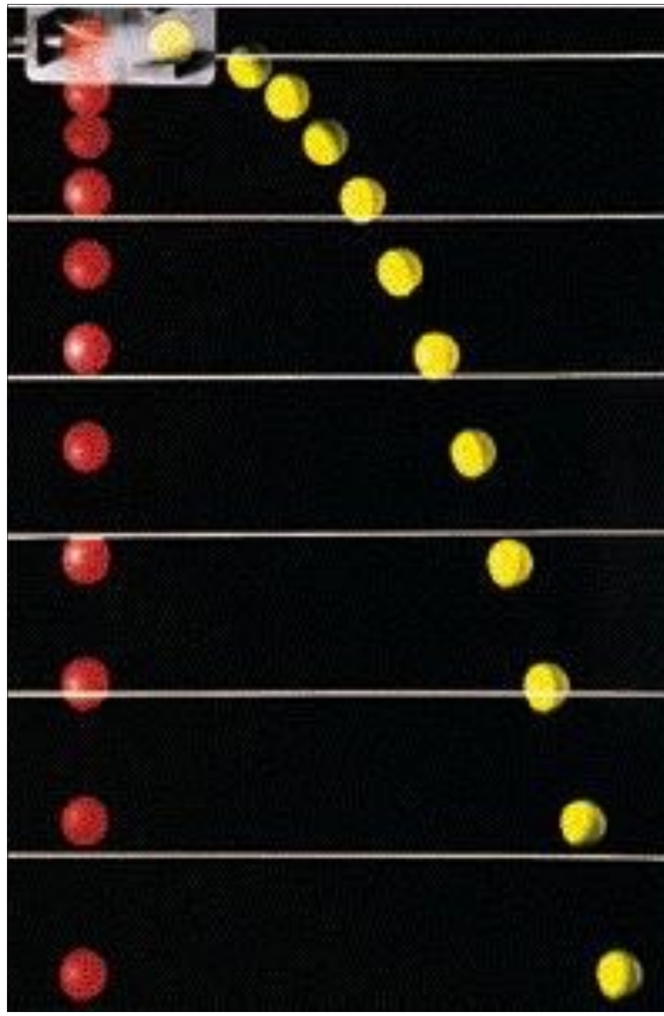
ANSWER 5

Givens (w/ SI units)	Applicable Equation	Plug & Chug
$v_i = 30\ m/s$ $a = -9.8\ m/s^2$ $v_f = 0\ m/s$	$v_f^2 = v_i^2 + 2\,a\,\Delta x$	$\Delta x = \frac{(0\ m/s)^2 - (30\ m/s)^2}{2\,(-9.8\ m/s^2)}$
	Solve Equation for Unknown	
Unknown	$\Delta x = \frac{v_f^2 - v_i^2}{2\,a}$	
$\Delta x = ?$		**Answer**: $\Delta x = 46\ m$

Once the ball reaches the top of the throw, its instantaneous velocity is zero, hence $v_f = 0$ m/s.

I'm taking upwards to be the positive direction and downwards to be the negative direction. v_i is positive because the ball is being thrown upwards, and *a* is negative because gravity is pulling the ball downwards. Keep track of direction and include negative signs where appropriate!

46 m is actually a bit unrealistic, because air resistance will slow down the ball considerably on its ascent. In real life, I'd expect to get closer to half of that



PROJECTILE MOTION

The horizontal and vertical components of projectile motion are completely independent of each other

In the diagram, the yellow ball is knocked to the right while the red ball is simply dropped. Both, however, approach the ground at the same rate.

Shoot-n-Drop - Harvard Natural Sciences Lecture Demonstrations, 2011
Click here to watch the video: https://www.youtube.com/watch?v=zMF4CD7i3hg

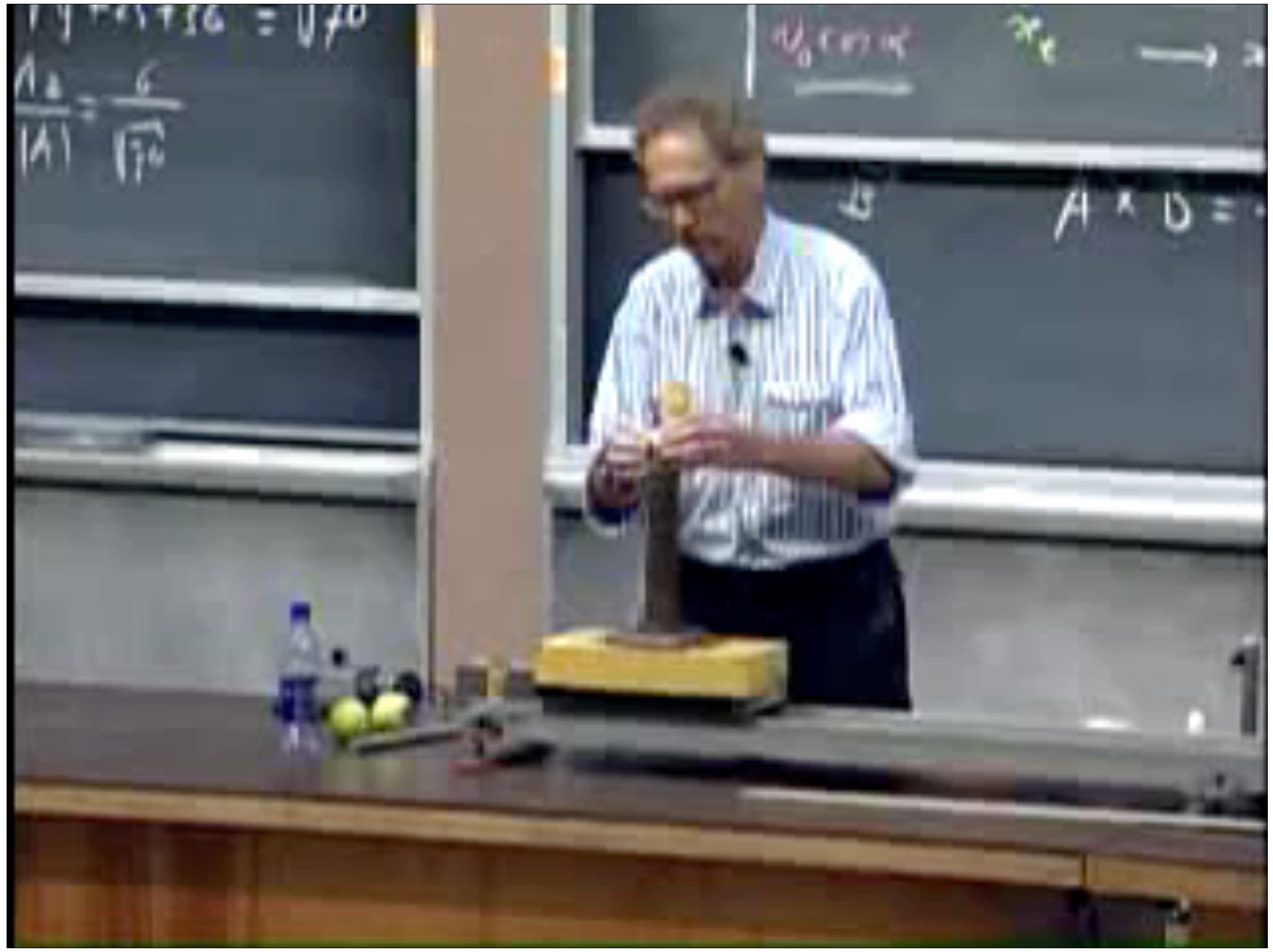
SANITY CHECK

➤ You're riding your Vespa down the street at a constant speed when a squirrel lands in your lap! You freak out and throw the squirrel straight up in the air (from your point of view) while you and your Vespa continue to travel forward at a constant speed. If air resistance is neglected, where will the squirrel land?

A. behind you

B. in front of you

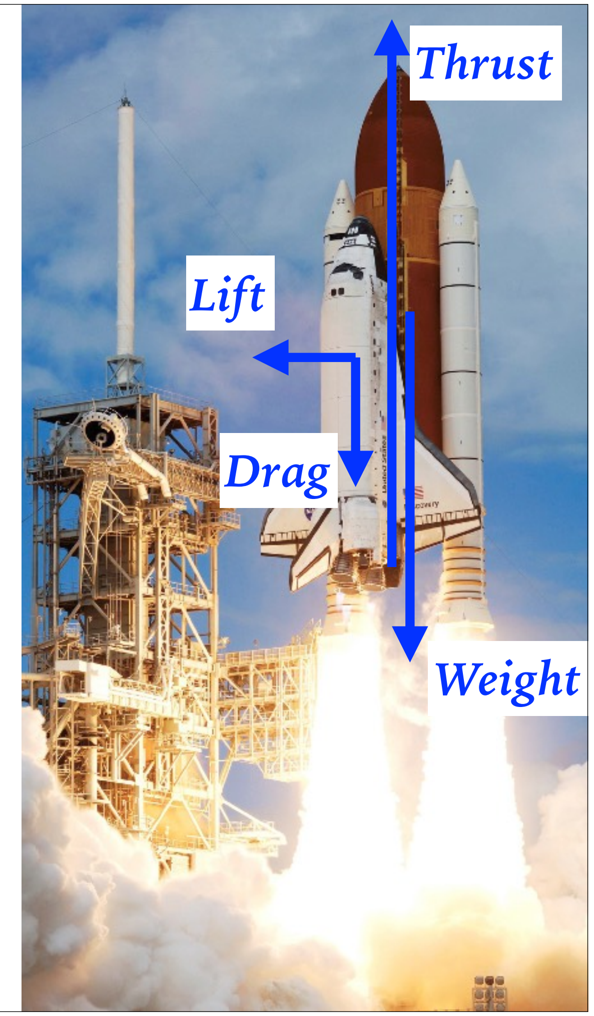
C. back in your lap



Horizontal velocity remains constant - Nitesh Batra, 2012
Click here to watch the video: https://www.youtube.com/watch?v=KacTRPL1MtE

CHAPTER 3: HOW ARE YOU GETTING THERE?

Dynamics — The Study of Why Things Move



Aristotle believed that for objects to maintain motion, they must have a force continuously exerted upon them and that the greater the force on the body, the greater the body's speed. Though that might seem intuitively correct, he was, as it turns out, quite wrong.

THE LAW OF INERTIA

Galileo realized that in the absence of friction, an object will continue at a constant speed in a straight line despite the fact no force is being applied! In fact, it is precisely because a force is being applied to it that the object slows down at all. Thus, friction is a force just like any other push or pull! This realization became the basis of the first law of motion.

> All objects will move in a straight line at a constant speed unless acted on by an external, unbalanced force
>
> *The First Law of Motion*

The First Law of Motion, also called the Law of Inertia, tells us how all objects naturally move:

- in a straight line at a constant (possibly zero) speed,

and also what is takes to change motion:

- an external, unbalanced force.

The force has to be both external AND unbalanced to change motion. An internal force is like trying to move a car from the inside by pushing on the steering wheel. A balanced force is like a tug-of-war game that ends in a tie. Both are forces, to be sure, but neither change motion because they aren't external AND unbalanced.

Inertia — a body's resistance to changes in its motion

Mass is the measure of an object’s inertia

- Mass and weight are not the same!

> The acceleration of an object is directly proportional to the net force acting on it and is inversely proportional to its mass
>
> *The Second Law of Motion*

To be *directly proportional* means as one quantity gets bigger, the other gets bigger. In this case, it means bigger net forces result in bigger accelerations. For example, doubling the force applied will double the rate of acceleration.

To be *inversely proportional* means as one quantity gets bigger, the other gets smaller. In this case, it means the bigger the mass of the object, the harder it is to accelerate. For example, an object with double the mass will accelerate at only half the rate.

$$F_{net} = ma$$

net force *is equal to* ***mass*** *times* ***acceleration***

It is far more common, however, to see the Second Law of Motion written as an equation: $F_{net} = ma$. This is the definition of *force*: any interaction that, when unopposed, will cause an object to accelerate.

CHAPTER: HOW ARE YOU GETTING THERE?

Forces is measured in *newtons* (N)

1 N = 1 kg•m/s^2

Force is also a vector, so pay attention to direction!

1 N = 1 kg•m/s^2, which, if you remember your dimensional analysis, you probably could have figured out on your own from the equation $F_{net} = ma$

Because force is a vector, two forces that act in the same direction create a net force equal to the sum of the forces, whereas two forces that act in opposite directions create a net force equal to the difference between the forces. Equal and opposite forces cancel out — they are balanced. When all the forces on an object are balanced, we say the object is in **equilibrium**.

> For every action there is an equal and opposite reaction
>
> *The Third Law of Motion*

Finally, the Third Law of Motion compares the forces between both objects involved in the interaction. If object A exerts a force on object B, object B automatically exerts an equal force back on object A. If you’ve ever stubbed your toe, then you’re already acquainted with the Third Law. When you kick the table, you exert a force on the table — maybe a force big enough to break the table! However, the table also exerts a force back on you — maybe a force big enough to break your toe! (I hope not)

(RE)ACTION

Situation	A rock in free fall
Action	The Earth pulls the rock down
Reaction	The rock pulls the Earth up

Situation	A bat knocks a baseball down center field
Action	The bat knocks the ball forward
Reaction	The ball knocks the bat backward

Situation	Inflating a party balloon
Action	The air pushes the balloon outwards
Reaction	The balloon pushes the air inwards

Situation	A rocket launches into the air
Action	The rocket pushes the exhaust down
Reaction	The exhaust pushes the rocket up

Notice the only differences between the action and reaction statements are that the subject and object are switched and the direction of the verb is made opposite.

NEWTON'S LAWS OF MOTION

I. All objects will move in a straight line at a constant speed unless acted on by an external, unbalanced force

II. $\mathbf{F}_{\text{net}} = m\mathbf{a}$

III. For every action there is an equal and opposite reaction

All three of the Laws of Motion, in one place.

EXAMPLE 6

Mad scientist Rick Sanchez and his grandson Morty need to accelerate their 1000 kg spaceship at ½ *g* in order to escape the Gazorpazorps. What net force is needed?

g refers to the acceleration due to gravity. $g = 9.8\ m/s^2$

ANSWER 6

Givens (w/ SI units)	Applicable Equation	Plug & Chug	
$m = 1000\ kg$ $a = \frac{1}{2} \cdot 9.8\ m/s^2$ $= 4.9\ m/s^2$	$F_{net} = ma$	$F_{net} = (1000\ kg)(4.9\ m/s^2)$	
	Solve Equation for Unknown		
Unknown	$F_{net} = ma$		
$F_{net} = ?$		**Answer**	$F_{net} = 4900\ N$

EXAMPLE 7

Rick and Morty escaped the Gazorpazorps and pull into the garage. The 1000 kg spaceship is brought to rest in the garage by a force of 8000 N. What is the net acceleration?

ANSWER 7

Givens (w/ SI units)	Applicable Equation	Plug & Chug	
$m = 1000\ kg$ $F_{net} = 8000\ N$	$F_{net} = ma$	$a = (8000\ N) / (1000\ kg)$	
	Solve Equation for Unknown		
Unknown	$a = F_{net} / m$		
$a = ?$		**Answer**	$a = 8\ m/s^2$

WEIGHT = FORCE OF GRAVITY

As mentioned before, mass and weight are not the same thing.

Weight = *mass* x *acceleration due to gravity*
or $F_g = mg$
where g = 9.8 m/s^2 near the surface of Earth

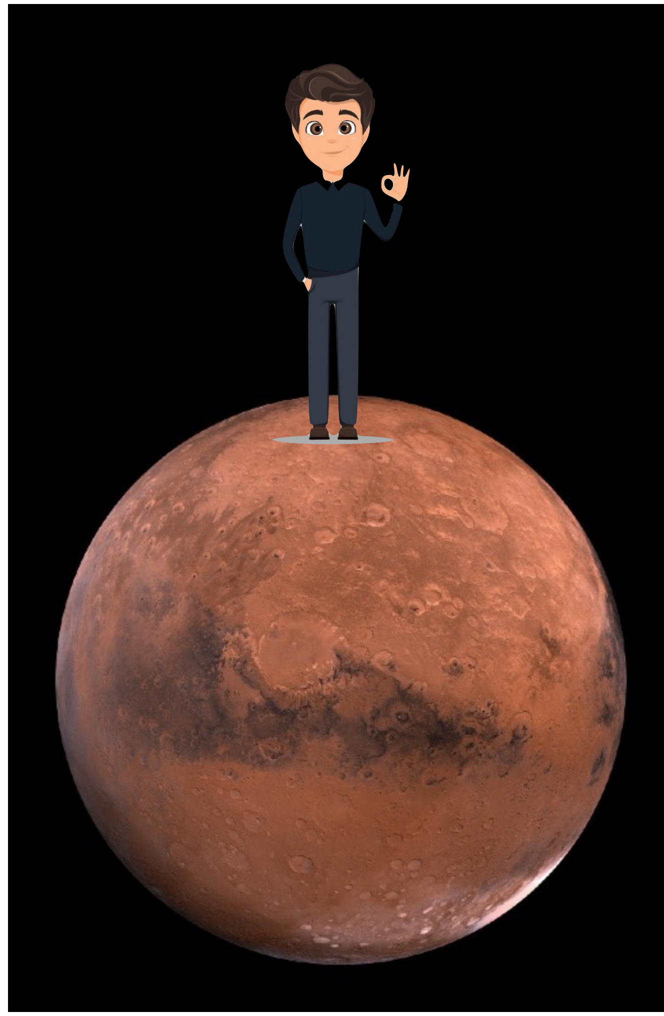
Your mass depends on how much stuff your body is made out of and is the same everywhere in the Universe. Your weight depends on how strong the gravity is that's pulling on you, so you'd weigh far less on the Moon than on Earth even though your mass would be the same in both places.

EXAMPLE 8A

Raphaldo weighs 700 N. What is his mass in kilograms?

ANSWER 8A

Givens (w/ SI units)	Applicable Equation	Plug & Chug	
$F_g = 700\ N$ $g = 9.8\ m/s^2$	$F_g = m\ g$	$m = (700\ N) / (9.8\ m/s^2)$	
	Solve Equation for Unknown		
Unknown	$m = F_{net} / g$		
$m = ?$		**Answer**	$m = 71\ kg$



EXAMPLE 8B

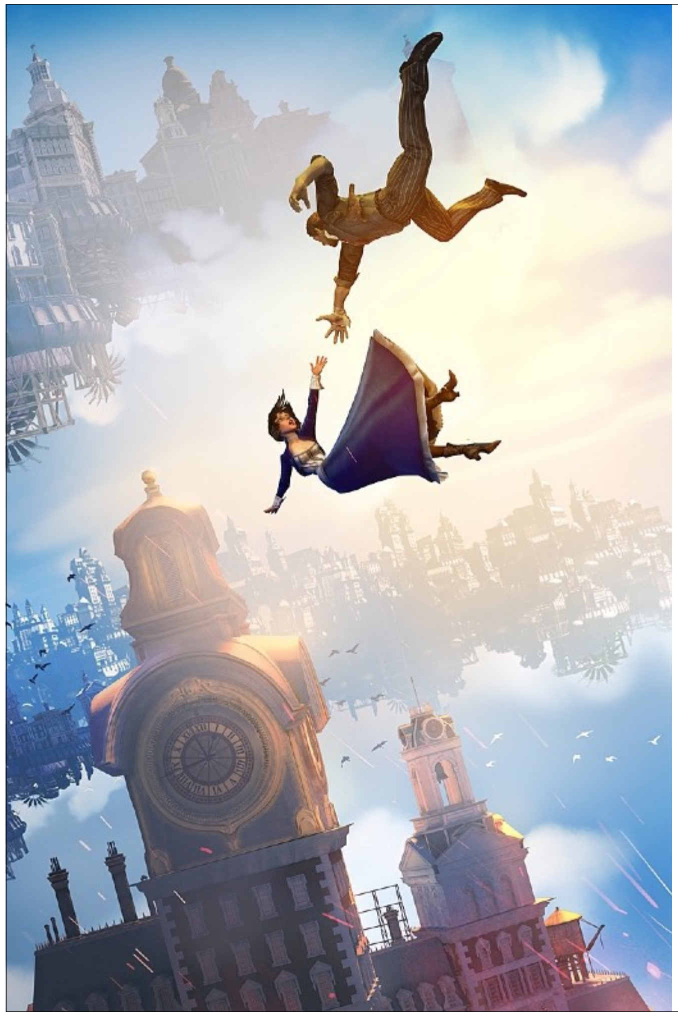
A mysterious alien abducts Raphaldo and whisks him away to Mars. For some reason they have a bathroom scale on the Red Planet, and Raphaldo decides to weigh himself. He finds his weight is only 263 N on Mars! What is the acceleration due to gravity on Mars?

ANSWER 8B

Givens (w/ SI units)	Applicable Equation	Plug & Chug
$F_g = 263\ N$ $m = 71\ kg$	$F_g = m\, g_{mars}$	$g_{mars} = (263\ N) / (71\ kg)$
	Solve Equation for Unknown	
Unknown	$g_{mars} = F_g / m$	
$g_{mars} = ?$		**Answer** $g_{mars} = 3.7\ m/s^2$

- Technically speaking, bathroom scales don't measure gravity, they measure how hard you are pushing into the scale. That contact force between you and the scale is called the *normal force*.
- The **normal force** is the component of a contact force that is perpendicular to the surface that an object contacts.
- In math and science, *normal* means *perpendicular*.

Bathroom scales operate under the assumption that, as long as you're just standing on the scale and not holding anything or using anything for support, the normal force between you and the scale will be equal to your weight.



SANITY CHECK

- Whether an object falls through the air or rests on a table, it is pulled down towards the Earth by the force of gravity
- What's the reaction force?

The Earth pulls the object down, the object pulls the Earth up — that's the action-reaction pair. For an object resting on a table, the force of gravity pulling it down and the normal force from the table pushing it up happen to be equal and opposite, but they are *not* an action-reaction pair. The normal force has its own action-reaction pair. Any guess what it is?

FRICTION

The resistance that one surface or object encounters when moving over another

Friction is another contact force, but one that runs parallel to the surfaces instead of perpendicular.

There are different types of friction:

kinetic

static

rolling

fluid

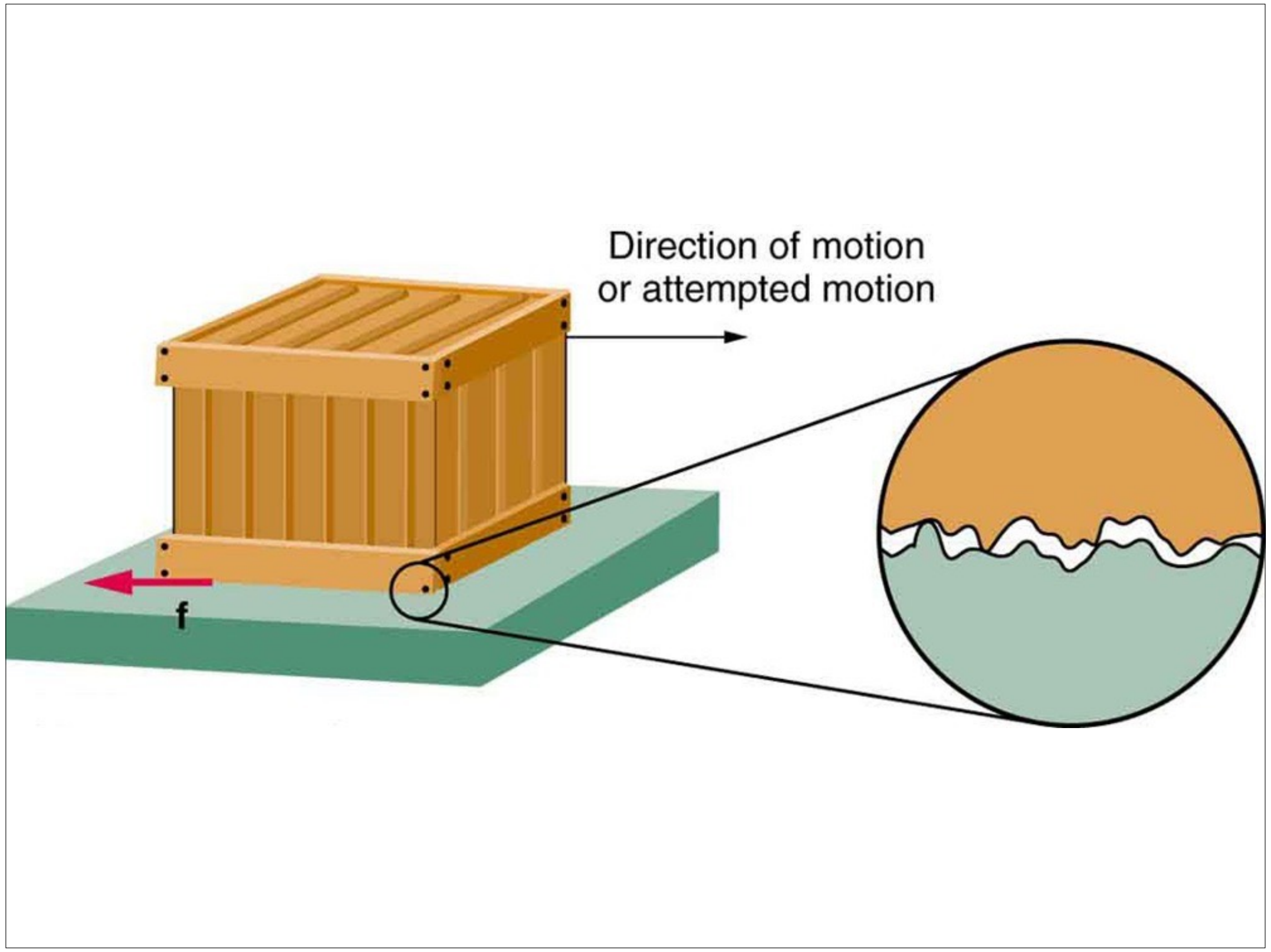
Friction always opposes motion

Kinetic friction, also called sliding friction, is friction experienced when one surface slides across another.

Static friction is when the objects experience sliding forces but haven’t started sliding yet.

Rolling friction is when one surface rolls across another.

Fluid friction refers to the drag forces experienced when an object moves through a gas or liquid. E.g. air resistance.



In all cases, the source of friction is the same: collisions. No surface is perfectly smooth, so as one surface slides along another, all the imperfections knock into each other along the way, slowing down the objects’ attempting to slide.

FRICTION

- What factors affect the force of friction?

Surprisingly, surface area and speed don't matter to friction! The only things that affect the force of friction are

1) the relative roughnesses of the surfaces
2) how hard the surfaces are pressing into each other, i.e. the normal force

$$F_{\mathrm{fr}} = \mu F_{\mathrm{N}}$$

the force of ***friction*** *equals the* ***coefficient of friction***
times the ***normal*** *force*

The coefficient of friction (μ) is a quantity the describes the relative roughnesses of the surfaces. The bigger μ is, the rougher the surfaces. μ has no units and is always greater than zero and usually less than one.

EXAMPLE 9

A 525 kg car drives along the road and experiences a coefficient of friction of 0.62. What is the force of friction on the car?

ANSWER 9

Givens (w/ SI units)	Applicable Equation	Plug & Chug
$m = 525\ kg$ $\mu = 0.62$	$F_{fr} = \mu F_N$ $F_N = F_g$ $F_g = mg$	$F_{fr} = (0.62)(525\ kg)(9.8\ m/s^2)$
Unknown	**Solve Equation for Unknown**	
$F_{fr} = ?$	$F_{fr} = \mu mg$	**Answer** $F_{fr} = 3{,}190\ N$

The equation for friction requires us to know the normal force, but we were only given the mass. However, we know that because the car isn't accelerating up or down, the normal force must be equal to the force of gravity.

EXAMPLE 10

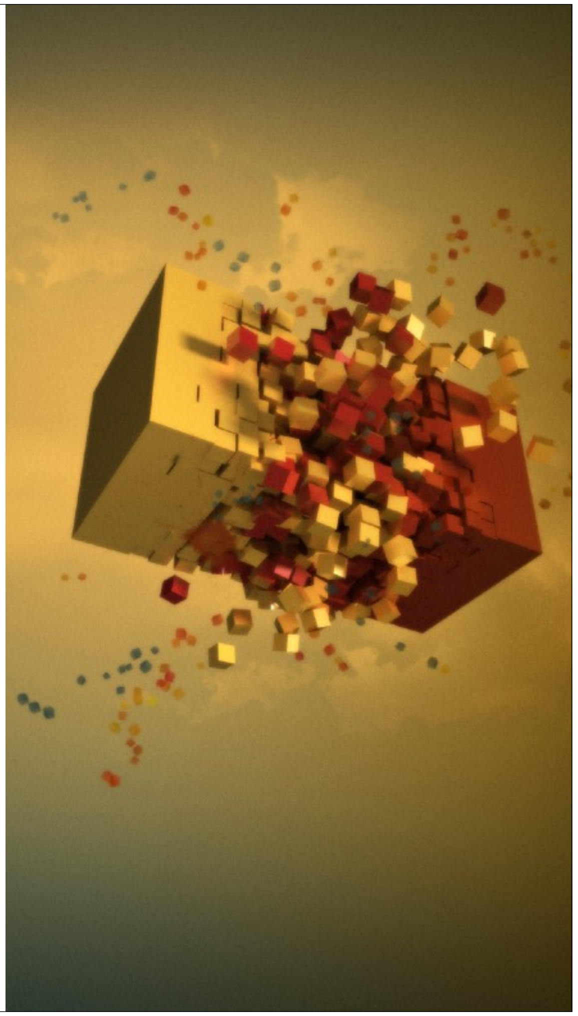
A child drags a 48 kg sled across the snow. She must apply a 175 N force in order to overcome friction. What is the coefficient of friction between the sled and the snow?

ANSWER 10

Givens (w/ SI units)	Applicable Equation	Plug & Chug	
$m = 48\ kg$ $F_{fr} = 172\ N$	$F_{fr} = \mu F_N$ $F_N = F_g$ $F_g = mg$	$\mu = \frac{(172\ N)}{(48\ kg)(9.8\ m/s^2)}$	
	Solve Equation for Unknown		
Unknown	$\mu = \frac{F_{fr}}{mg}$		
$\mu = ?$		**Answer**	$\mu = 0.37$

CHAPTER 4: WHAT IF SOMETHING GETS IN THE WAY?

Collisions & Conservation of Momentum



MOMENTUM

The quantity of motion

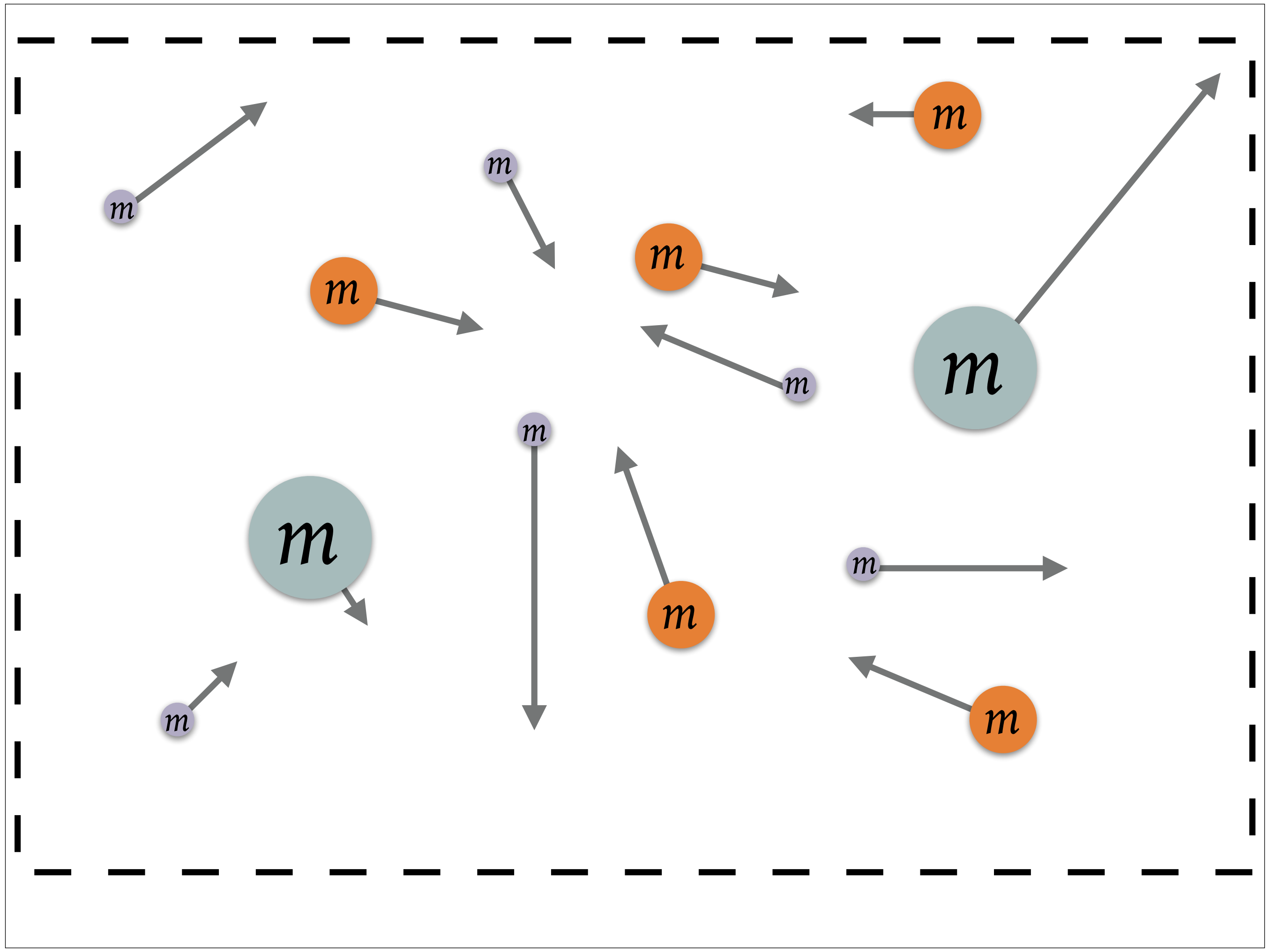
Momentum is at the heart of understanding collisions.

$$p = mv$$

an object's ***momentum*** *is equal to the product of its* ***mass*** *&* ***velocity***

- The plural of *momentum* is *momenta*.
- Momentum is measured in kg•m/s
- It is also a vector, so pay attention to the direction.

If you take the time to measure and calculate the momenta of objects colliding with each other, you will discover something pretty amazing…



Take as many or few objects as you want and find the momentum of each object. Calculate the total momentum of the entire system, keeping in mind that momenta in opposite directions cancel out. Then let the objects move and collide, and afterwards repeat the process using the new momenta of the objects to recalculate the total momentum of the system. Repeat this whole process as many times as you want, and you'll find that the number you calculate for the total momentum comes out the same every time. Individual momenta might change, but as long as nothing leaves the system and nothing new enters, the total momentum will not change.

> The total momentum of an isolated system remains constant
>
> *The Law of Conservation of Momentum*

In science, when we say something is conserved, we mean it stays the same.

This law is only true of *isolated* systems — that is, isolated from external, unbalanced forces. Remind you of anything?

SANITY CHECK

You drop a rock and allow it to plummet in free fall. Is momentum conserved?

It is if you include the Earth. If you don't include the Earth in your system, then gravity is an external, unbalanced force, and our system isn't isolated. However, if you include both the rock and the planet in your system, then gravity is an internal force, and you see how the downward motion of the rock is balanced out by the upward motion of the Earth.

COLLISIONS

- *Elastic Collision* — a collision during which no deformation takes place (or at least very little)
- *Inelastic Collision* — a collision during which deformation takes place
- *Perfectly Inelastic Collision* — a collision where the objects stick together after colliding

Pool balls bouncing off each other is a good example of an elastic collision. Two balls of clay, however, are more likely to stick together upon colliding, which would be a perfectly inelastic collision.

CONSERVATION OF MOMENTUM CALCULATIONS

Conservation of momentum for collisions between *n* number of objects:

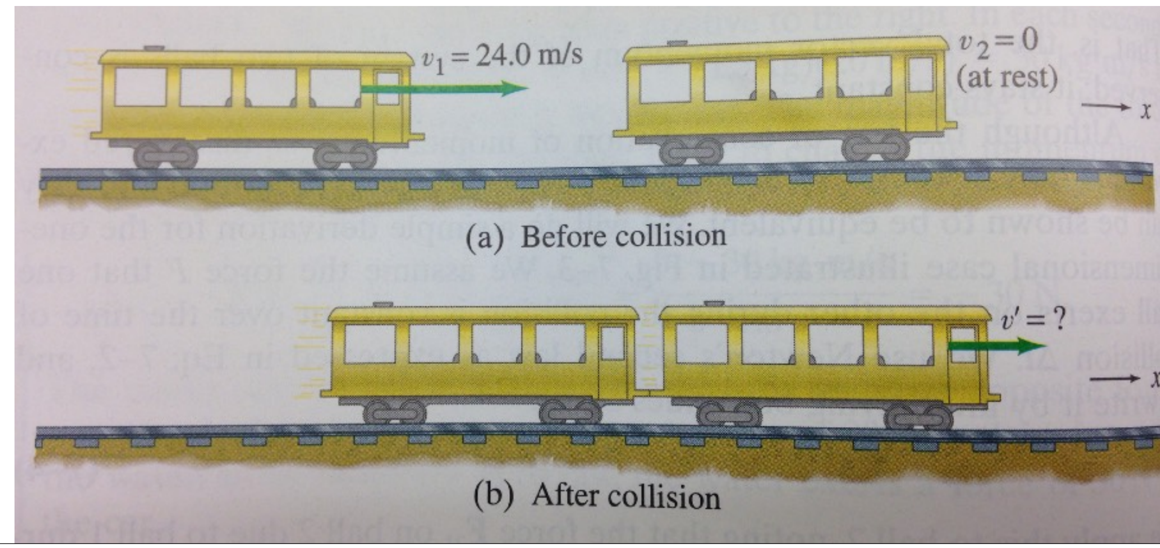
Total momentum before the collision		Total momentum after the collsion
$p_{1,i} + p_{2,i} + \ldots + p_{n,i}$	=	$p_{1,f} + p_{2,f} + \ldots + p_{n,f}$

Conservation of momentum for two object collisions:

Inelastic collision	Elastic collision
$m_1v_1 + m_2v_2 = (m_1 + m_2)v_f$	$m_1v_1 + m_2v_2 = m_1v_{1,f} + m_2v_{2,f}$

EXAMPLE 11

A 10,000 kg railroad car traveling at a speed of 24.0 m/s strikes an identical car at rest. If the cars lock together as a result of the collision, what is their common speed afterwards?



- Answer: $v_f = 12$ m/s

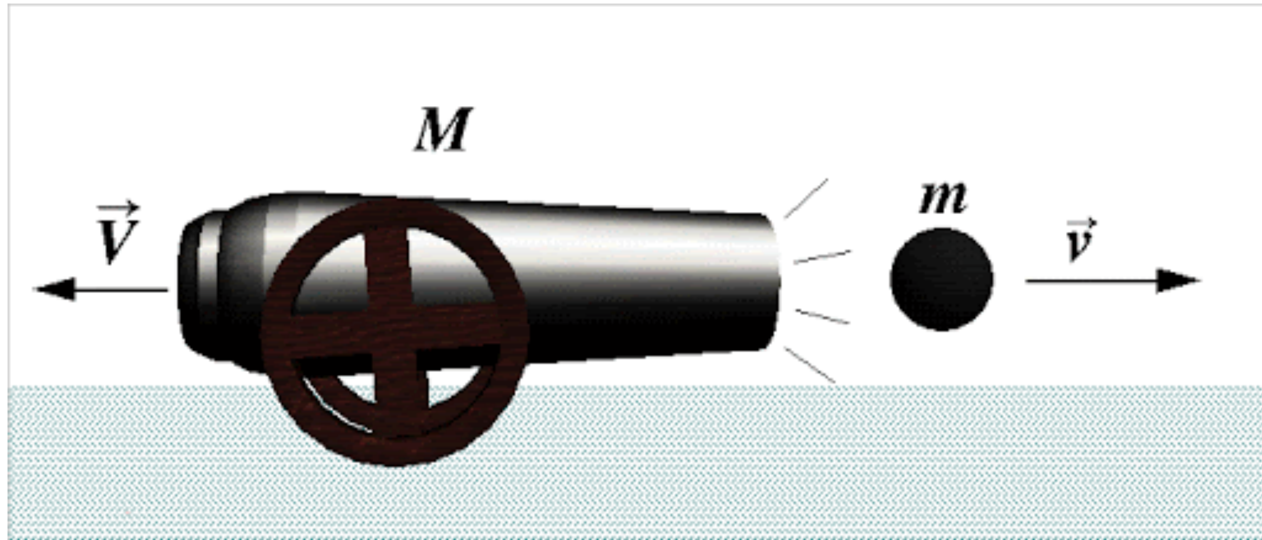
ANSWER 11

Givens (w/ SI units)	Applicable Equation	Plug & Chug	
$m_1 = 10{,}000\ kg$ $v_1 = 24\ m/s$ $m_2 = 10{,}000\ kg$ $v_2 = 0\ m/s$	$m_1v_1 + m_2v_2 = (m_1 + m_2)v_f$	$v_f = \frac{[(10{,}000\ kg)(24\ m/s) + (10{,}000\ kg)(0\ m/s)]}{[(10{,}000\ kg) + (10{,}000\ kg)]}$	
	Solve Equation for Unknown		
Unknown	$v_f = \frac{m_1v_1 + m_2v_2}{(m_1 + m_2)}$		
$v_{final} = ?$		**Answer**	$v_f = 12\ m/s$

Initially all the momentum is with the first car. After they collide and stick together, they share the momentum, and, since they are both the same mass, they split the momentum evenly. The final speed is half the initial speed because now there is twice as much mass moving as before, but the total momentum is still the same.

Conservation of momentum applies any time there is an interaction between objects, whether it's two separate things that collide together or two things that start together and blow apart. An explosion is essentially a perfectly inelastic collision in reverse.

In the case of the space shuttle, initially everything is at rest on the platform. After ignition, the shuttle and fuel exhaust explode apart launching the shuttle upward. The shuttle gains upward momentum, which balances out with the downward momentum the exhaust gains. The total momentum is still zero.



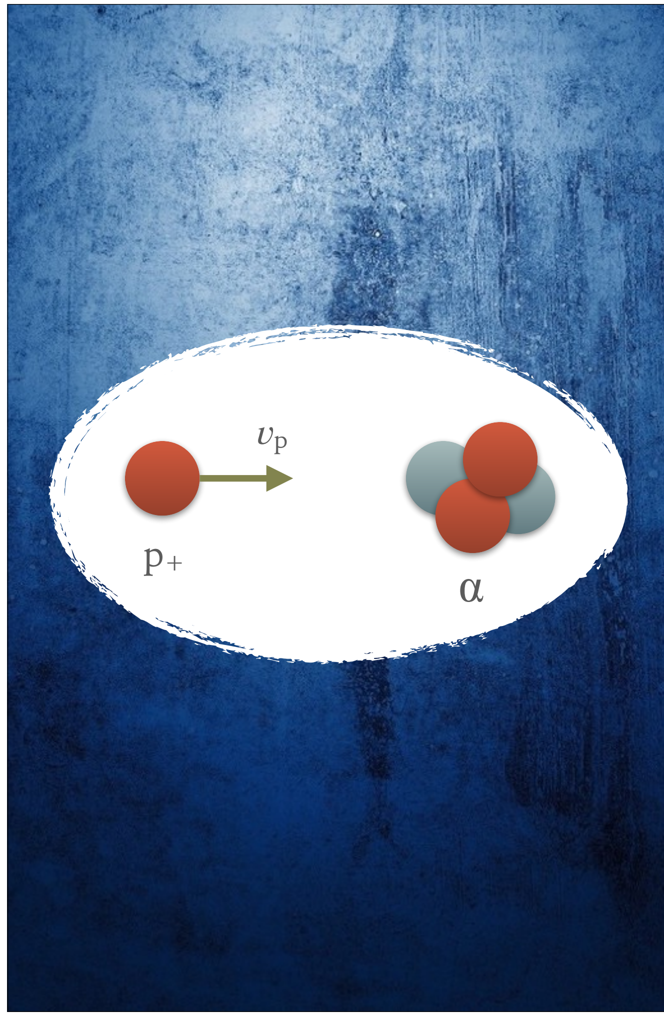
When a cannon fires, the forward momentum of the cannonball is matched by the recoil of the cannon.

EXAMPLE 12

What is the recoil velocity of a 5,000-kg cannon that shoots a 50.0-kg cannonball at a speed of 120 m/s?

ANSWER 12

Givens (w/ SI units)	Applicable Equation	Plug & Chug
$m_1 = 5{,}000\ kg$ $m_2 = 50\ kg$ $v_i = 0\ m/s$ $v_2 = 120\ m/s$	$(m_1 + m_2)v_i = m_1v_1 + m_2v_2$	$v_1 = \frac{[(5{,}000\ kg) + (50\ kg)](0\ m/s) - (50\ kg)(120\ m/s)}{(5{,}000\ kg)}$
Unknown	**Solve Equation for Unknown**	
$v_1 = ?$	$v_1 = \frac{(m_1 + m_2)v_i - m_2v_2}{m_1}$	**Answer**: $v_1 = -1.2\ m/s$



EXAMPLE 13

- A proton of mass m_p = 1.67×10^{-27} kg traveling with a speed of 3.60×10^4 m/s has an elastic head-on collision with an alpha particle (a helium nucleus; m_α = 6.64×10^{-27} kg) initially at rest.
- If the proton rebounds with a velocity of 2.15×10^4 m/s, how fast must the alpha particle be moving after the collision?

ANSWER 13

Givens (w/ SI units)	Applicable Equation	Plug & Chug
$m_p = 1.67 \times 10^{-27}$ kg $v_p = 3.60 \times 10^{4}$ m/s $m_\alpha = 6.64 \times 10^{-27}$ kg $v_\alpha = 0$ m/s $v_p' = -2.15 \times 10^{4}$ m/s	$m_p v_p + m_\alpha v_\alpha = m_p v_p' + m_\alpha v_\alpha'$	$v_\alpha' = [(1.67 \times 10^{-27}\text{ kg})(3.60 \times 10^{4}\text{ m/s}) + (6.64 \times 10^{-27}\text{ kg})(0\text{ m/s}) - (1.67 \times 10^{-27}\text{ kg})(-2.15 \times 10^{4}\text{ m/s})] \div (6.64 \times 10^{-27}\text{ kg})$
Unknown	**Solve Equation for Unknown**	
$v_\alpha' = ?$	$v_\alpha' = \dfrac{m_p v_p + m_\alpha v_\alpha - m_p v_p'}{m_\alpha}$	**Answer**: $v_\alpha' = 14{,}500$ m/s

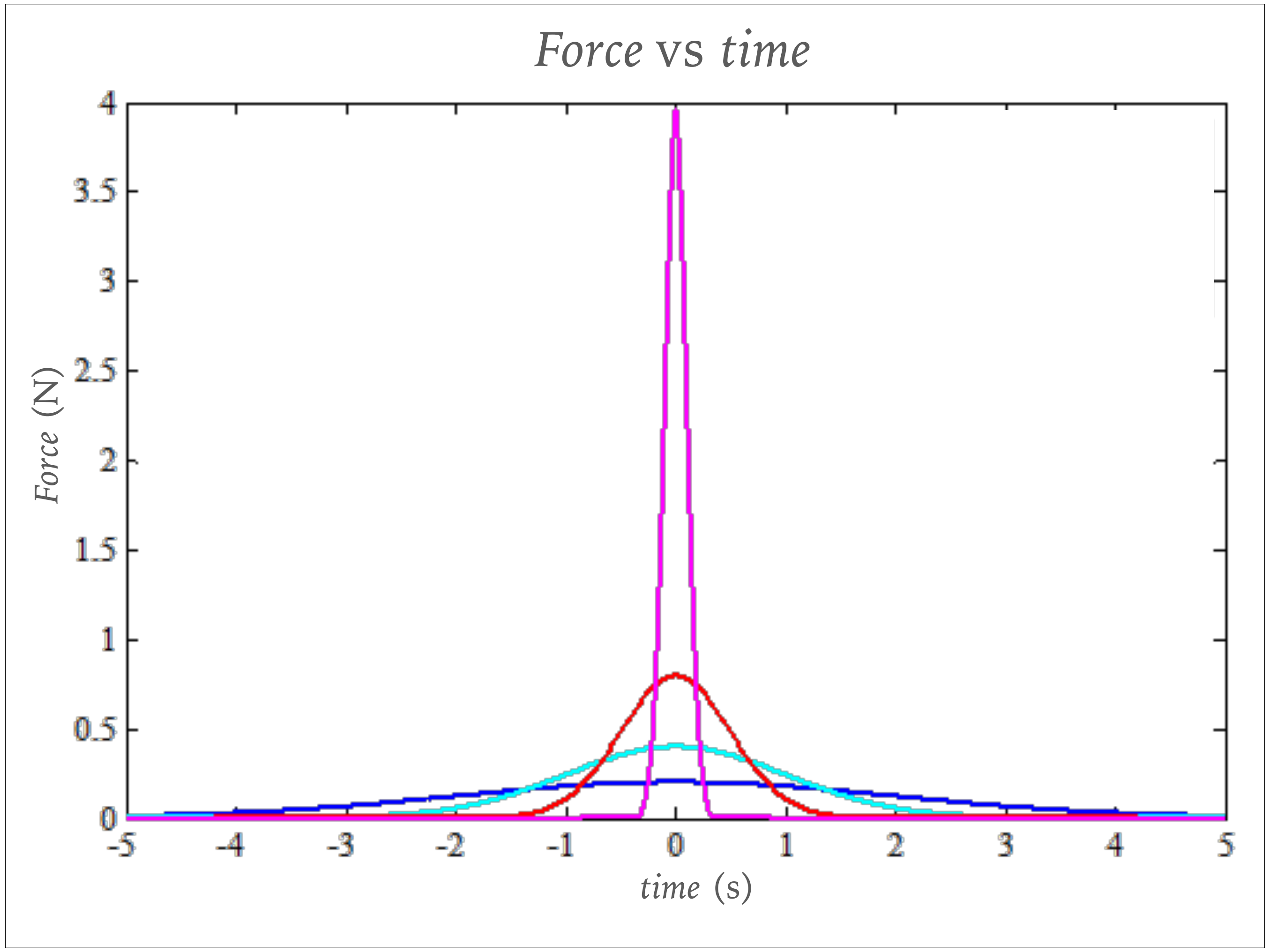
Notice that v_p' is negative to indicate that the proton is moving in the opposite direction after the collision than it was before.

Impulse

$$\Delta p = F_{net}\,\Delta t$$

*change in **momentum** = the product of **net force** and **time***

An interaction which changes the momentum of an object is called an **impulse** (**J**). Impulse is equal to the product of force and time and is measured in N•s.



These four curves represent four different forces applied for different amount of time. The blue curve represents a small force applied for a long amount of time, while the magenta curve represents a large force applied only briefly.

On a Force vs Time graph, impulse is represented by the area between the colored curves and the x-axis. In this case, the area beneath all four curves is the same! All four would change the momentum by the same amount.

SANITY CHECK

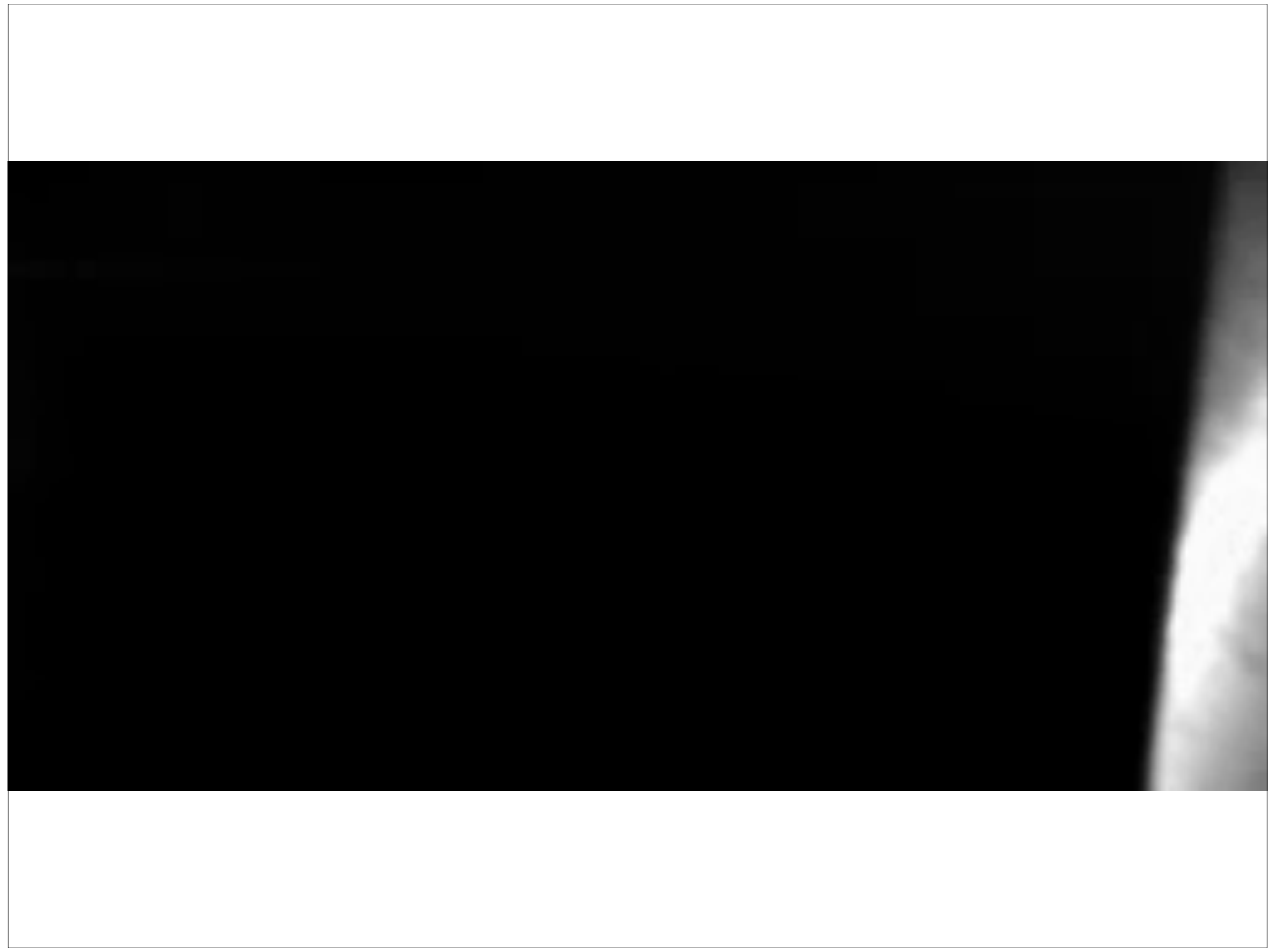
- You fall out of a first story window. Explain in terms of impulse, momentum, etc. the difference between hitting the ground with stiff legs vs. bent legs. If you can, which way should you hit the ground and why?

Once you fall, there's not much you can do to affect how *fast* you hit the ground, but you can control how *hard* you hit the ground. You want to hit the ground in whichever way takes the **most time** to bring you to a stop because that's the way that will require the **least force**.

SANITY CHECK

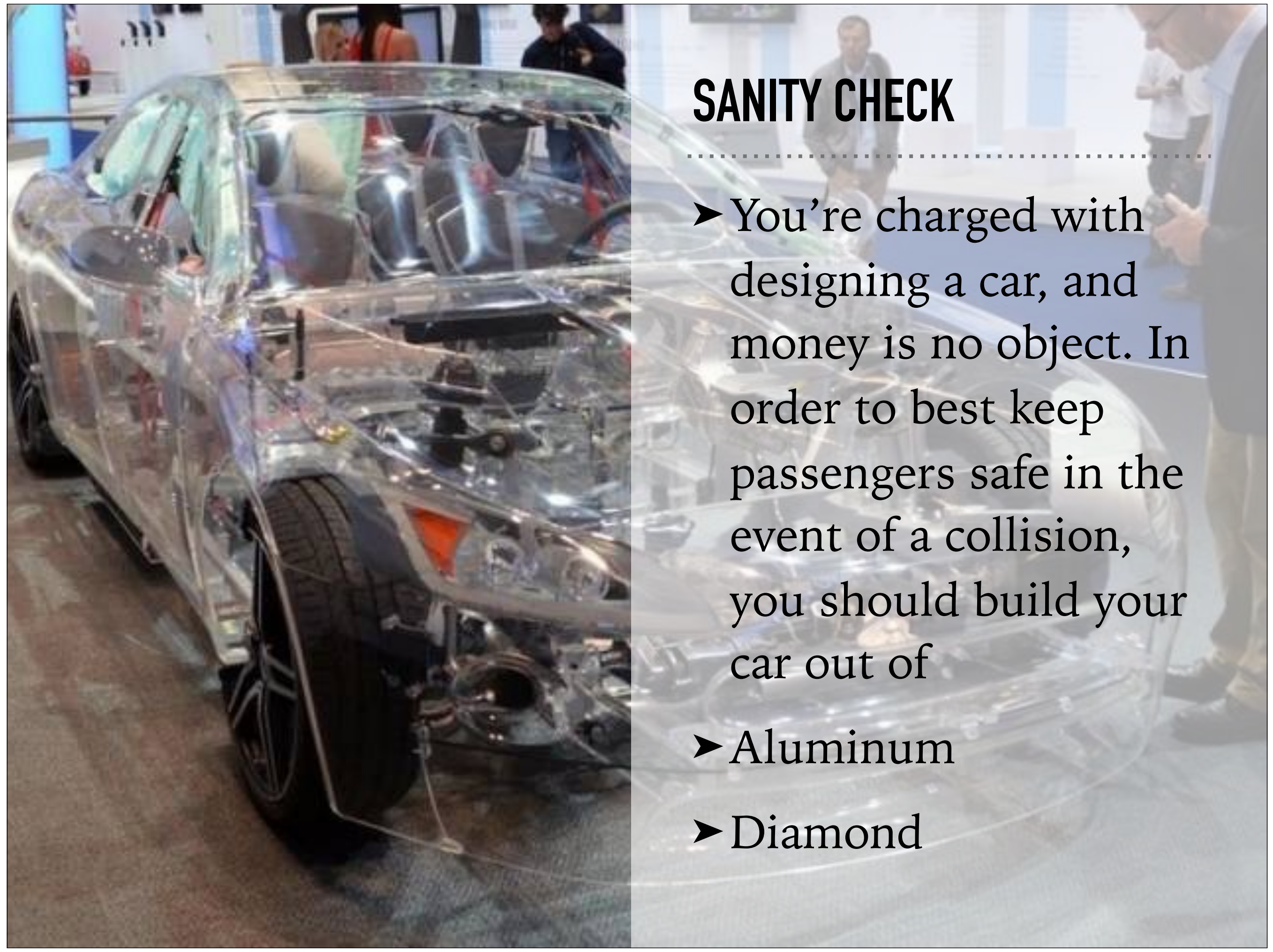
- Mario is cleaning up the town with his Flash Liquidizer Ultra Dousing Device, aka FLUDD.
- Will the force on the wall be different if the water splashes back vs. the water hits the wall and just slides down? How and why?

When two objects collide, both objects deform. Typically force jumps from zero to a very large value and back to zero in a short amount of time



- Golfball deformation
- Click here to watch the video: https://www.youtube.com/watch?v=00I2uXDxbaE

- Karate chop deformation
- Click here to watch the video: https://www.youtube.com/watch?v=otHZwjElXwQ



SANITY CHECK

- You're charged with designing a car, and money is no object. In order to best keep passengers safe in the event of a collision, you should build your car out of
- Aluminum
- Diamond

Understanding Car Crashes: It's Basic Physics — IIHS, 2020
Click here to watch the video: https://www.youtube.com/watch?v=2XKOzibVqJg