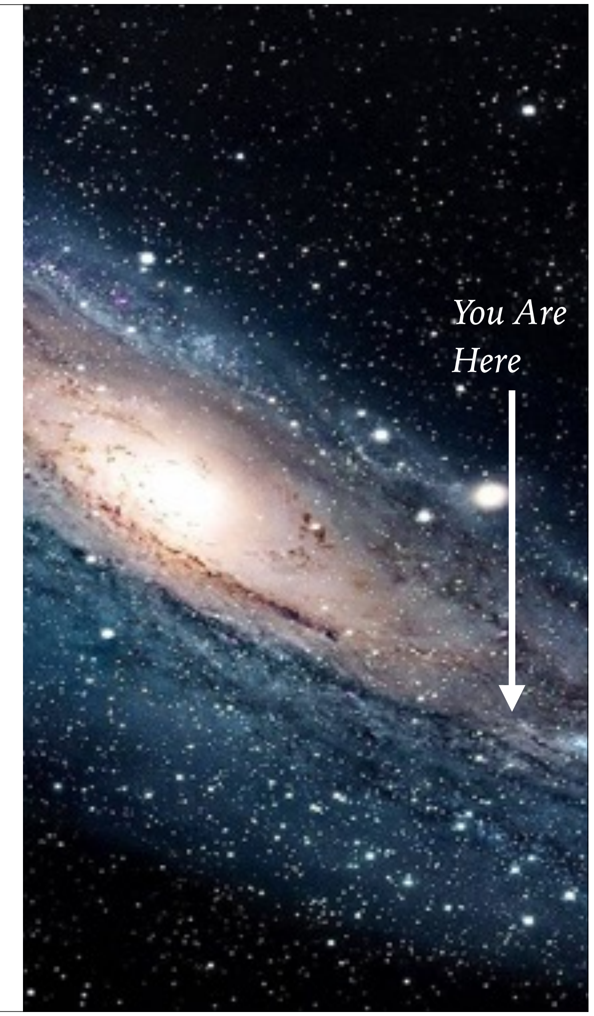
ACT II: FORCES & MOTION

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

SCENE I: WHERE ARE YOU?

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



SCENE I: WHERE ARE YOU?

- Write a description of your location

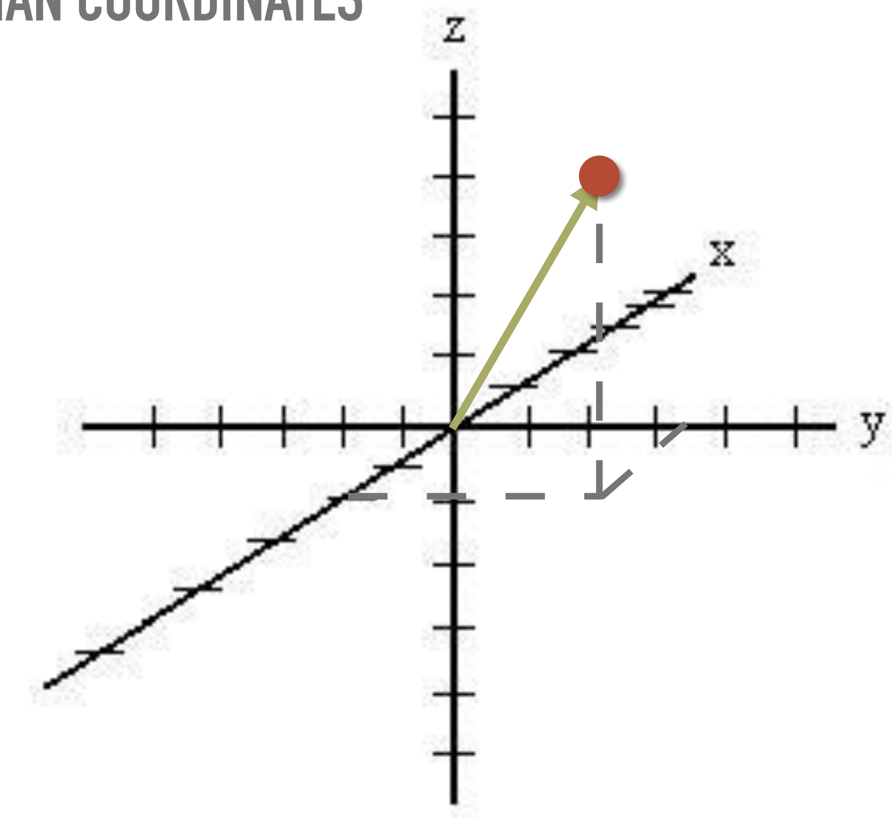
- e.g. 4463 Oak Grove Dr, Rm.323, La Cañada, CA 91011, United States of America, Earth, Solar System, Milky Way, Local Group, Virgo Supercluster, Universe
- Who wouldn’t be able to find you based on your description?
- Pick starting point, from there: how far to go and in what direction (e.g. *x, y, z*)

(Convenient)

3 WAYS TO DESCRIBE WHERE YOU ARE:

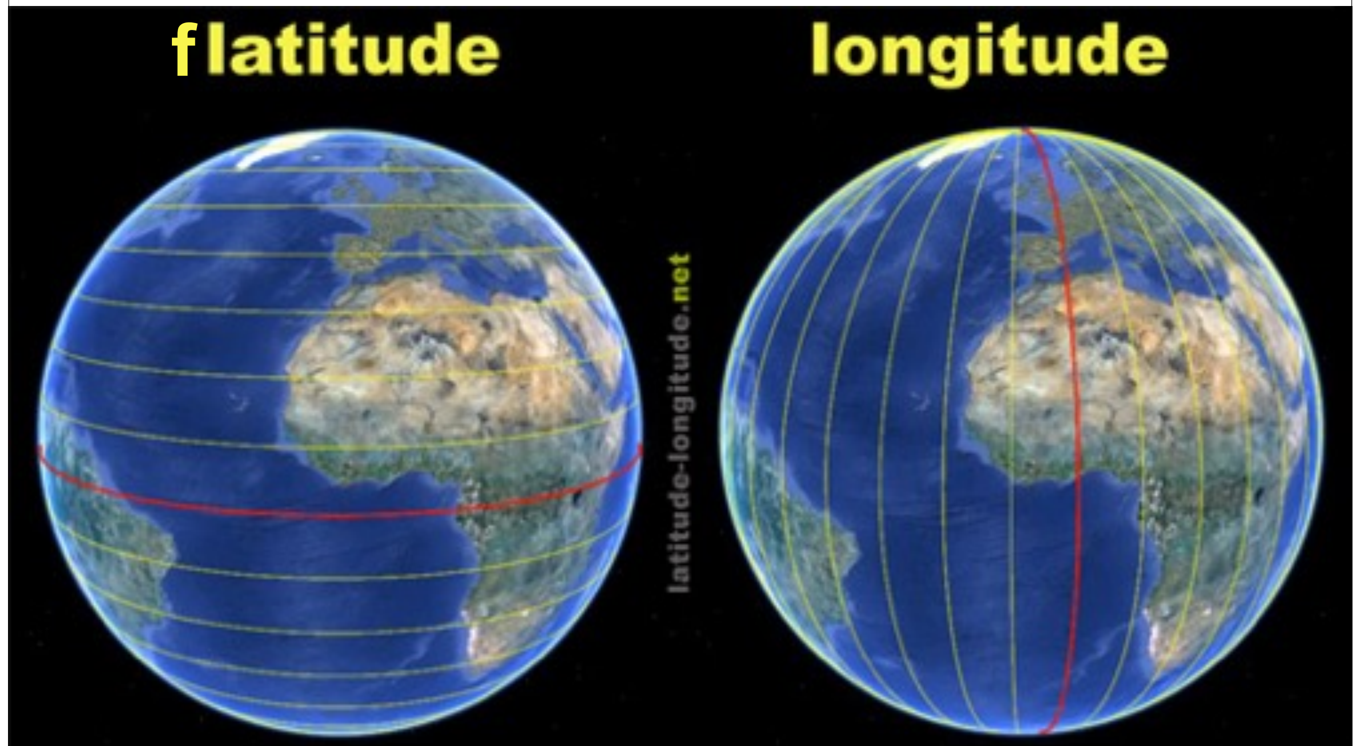
(and where you're going)

CARTESIAN COORDINATES

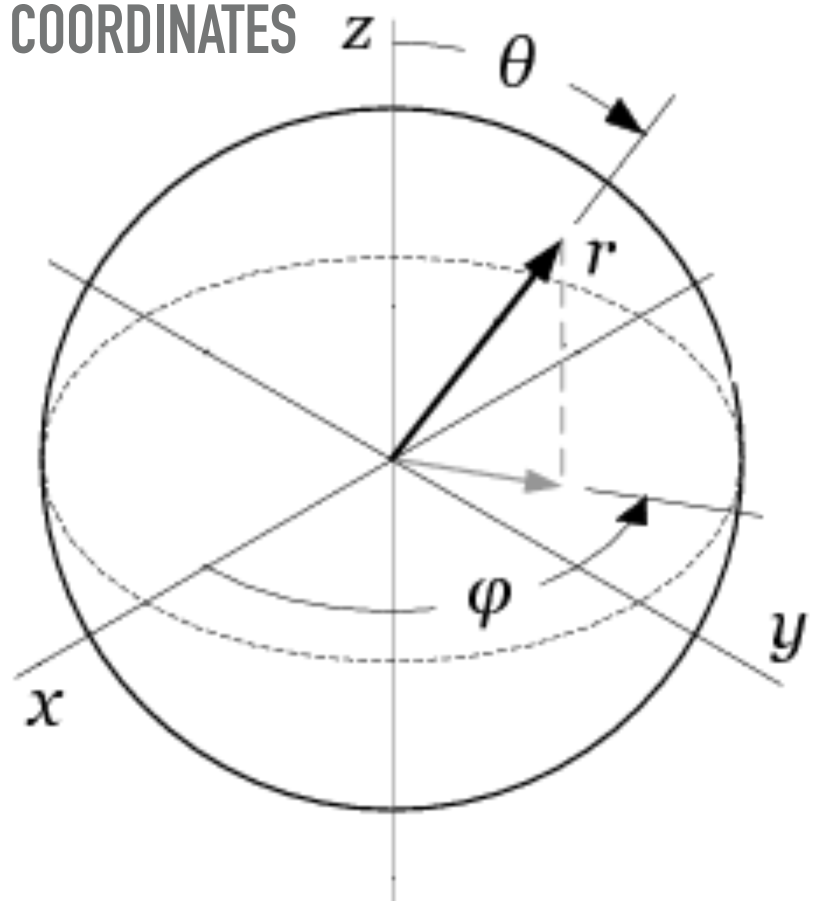


- Also called *rectangular coordinates*

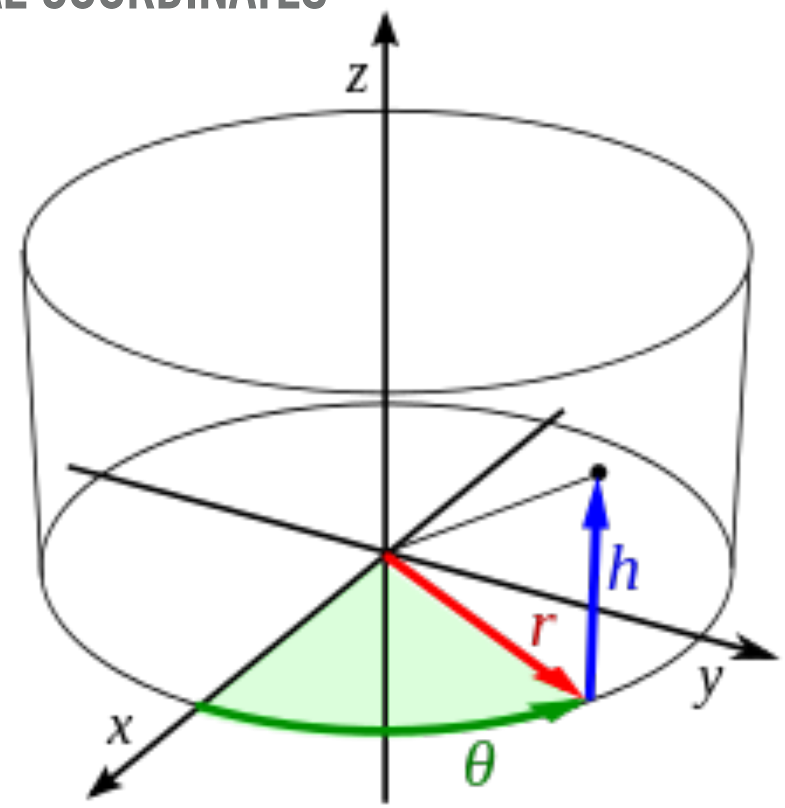

z
x
y

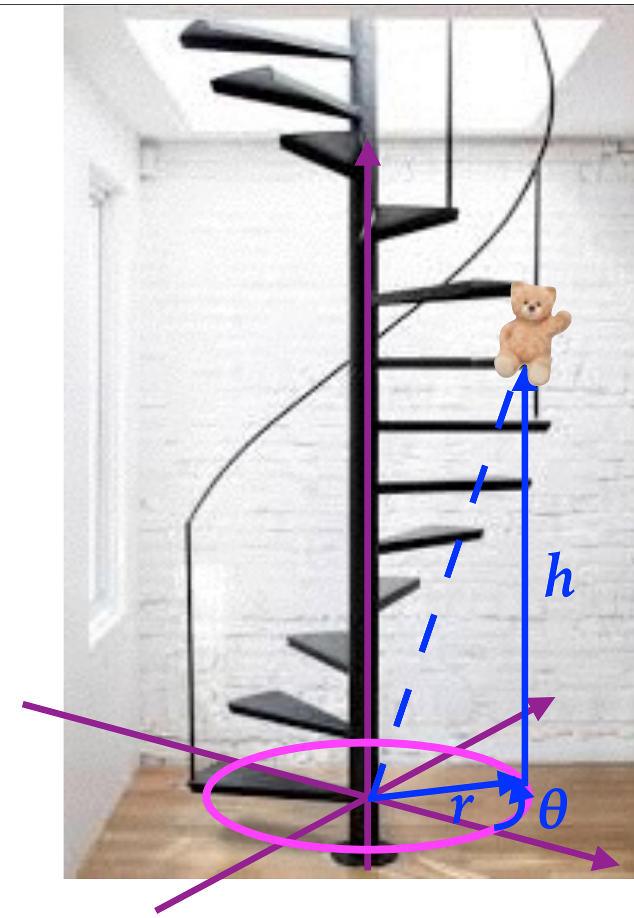

flatitude
longitude
latitude-longitude.net

SPHERICAL COORDINATES



CYLINDRICAL COORDINATES



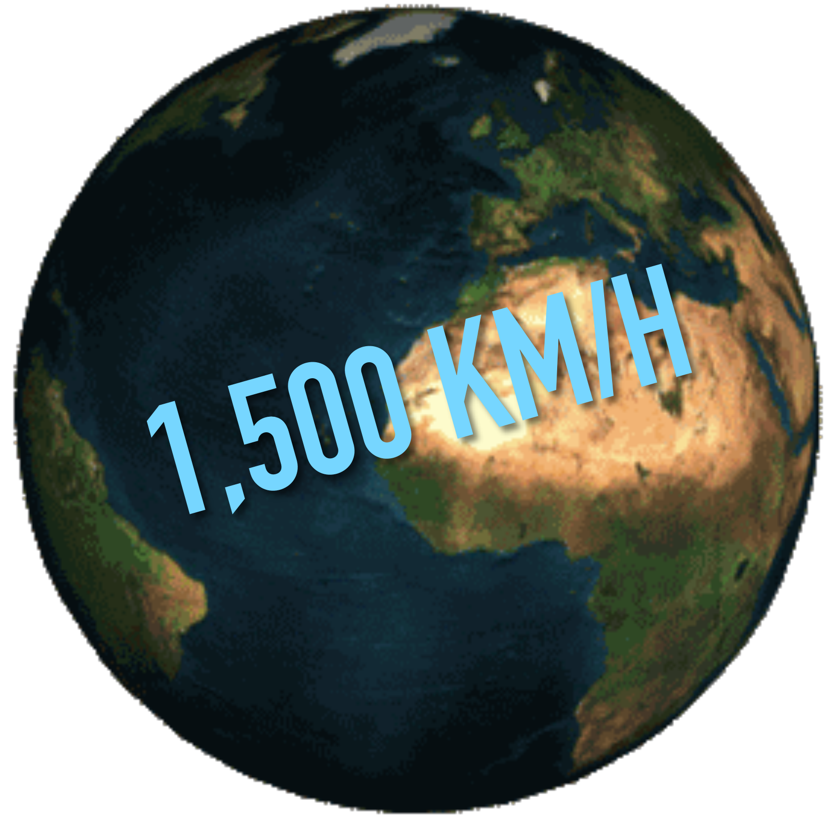


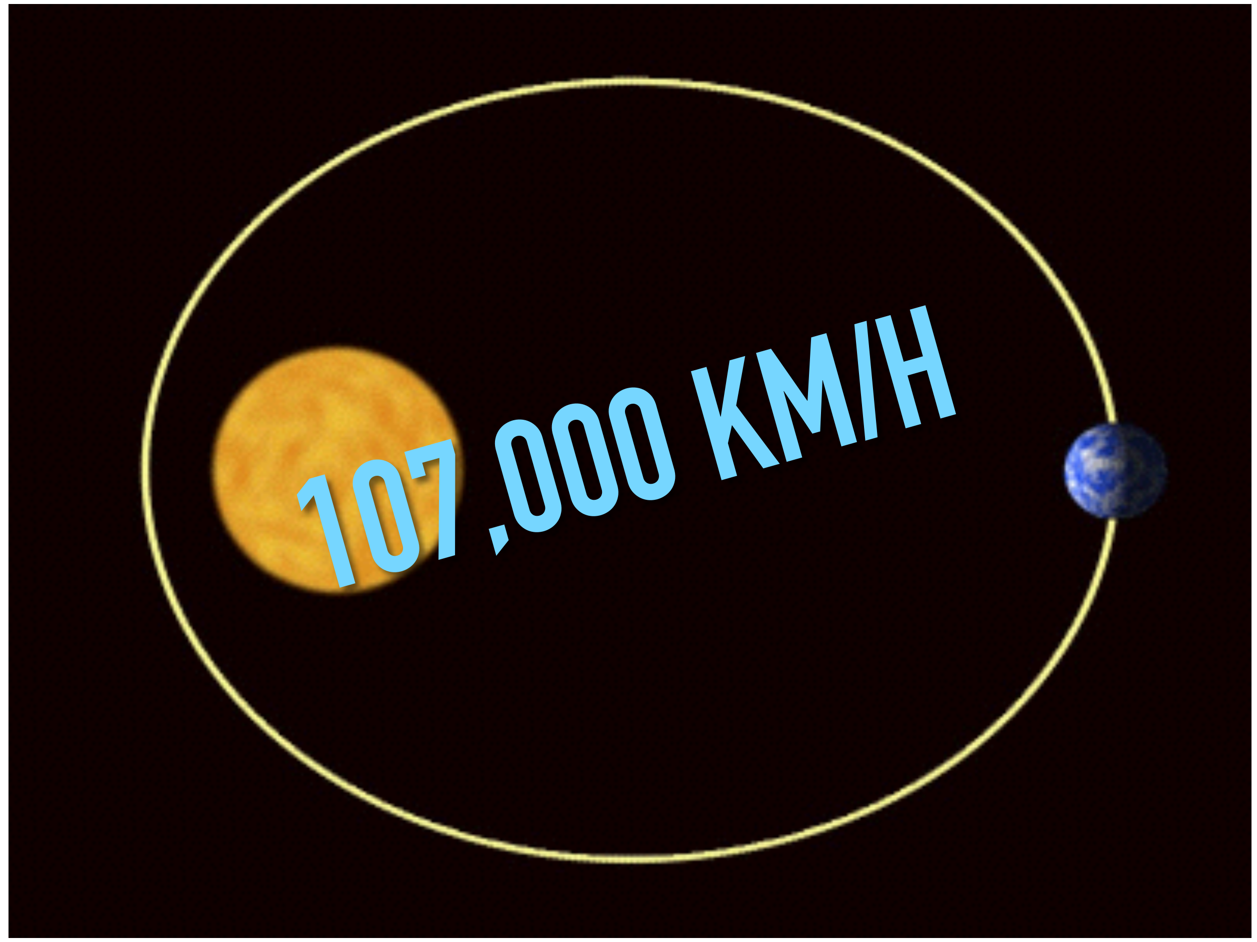
h
r
θ

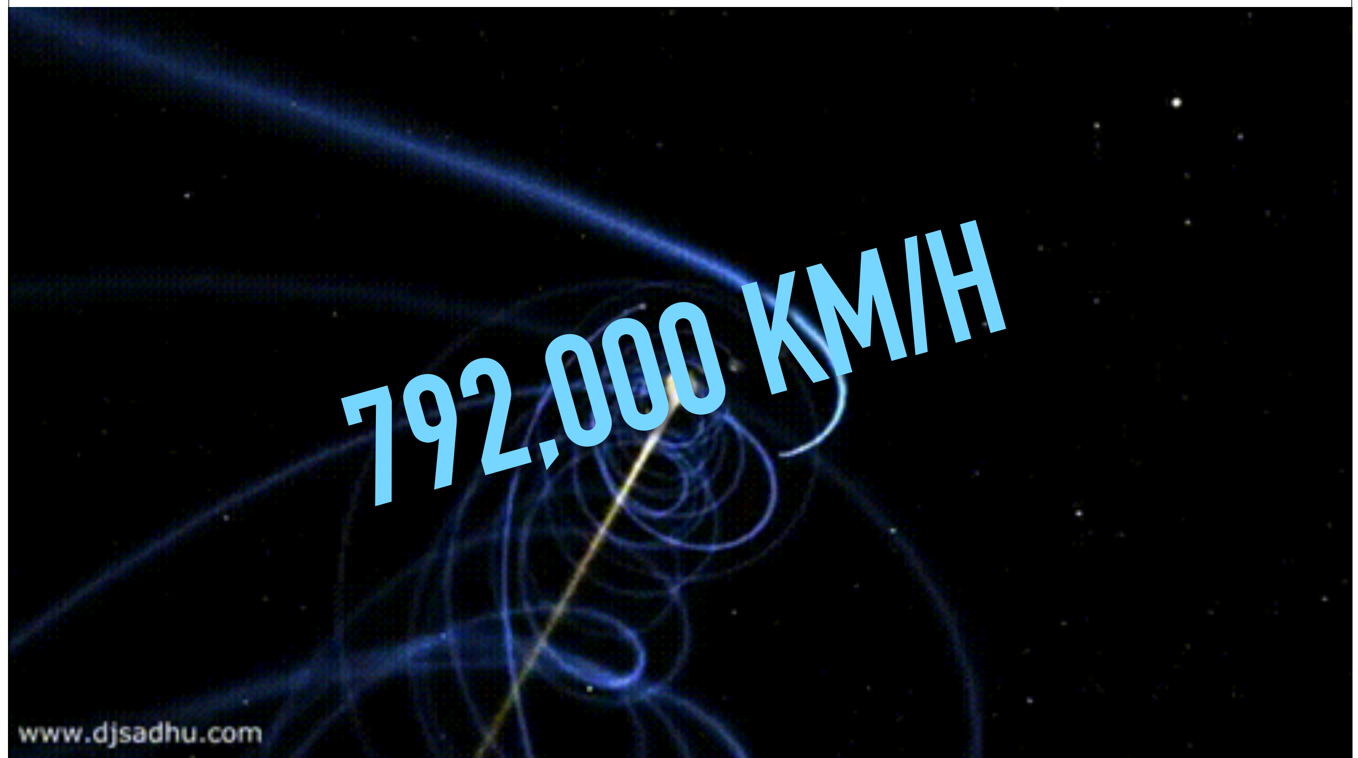
SCENE I: WHERE ARE YOU?

- 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!


1,500 KM/H


107,000 KM/H


792,000 KM/H
www.djsadhu.com

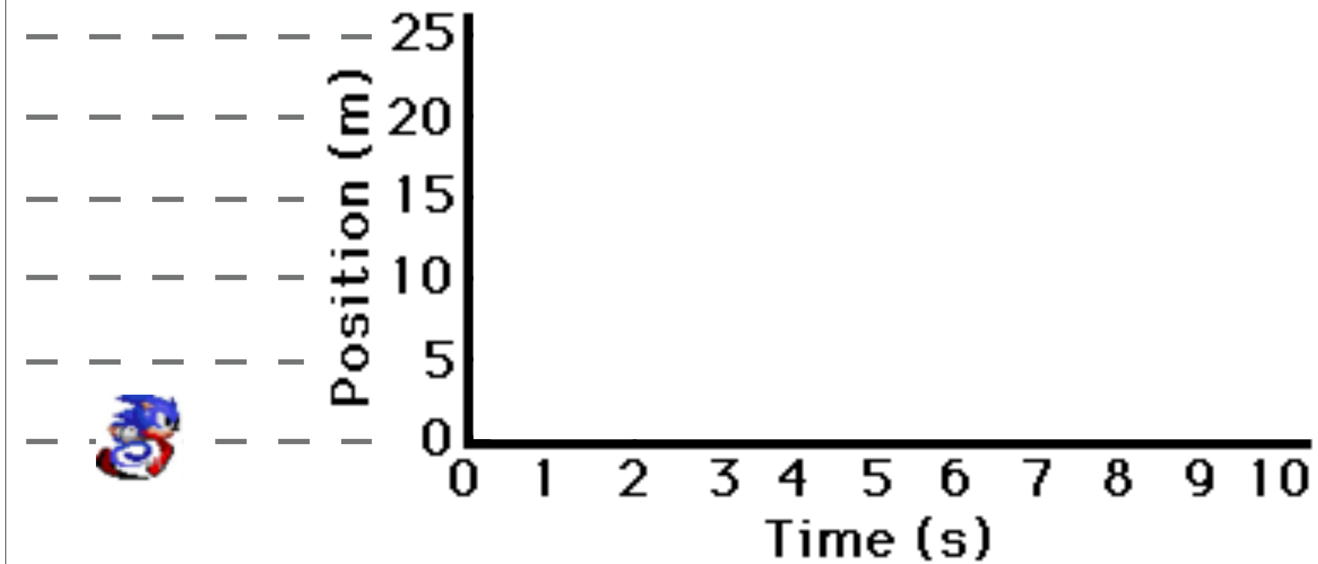

2.1 MILLION KM/H

“

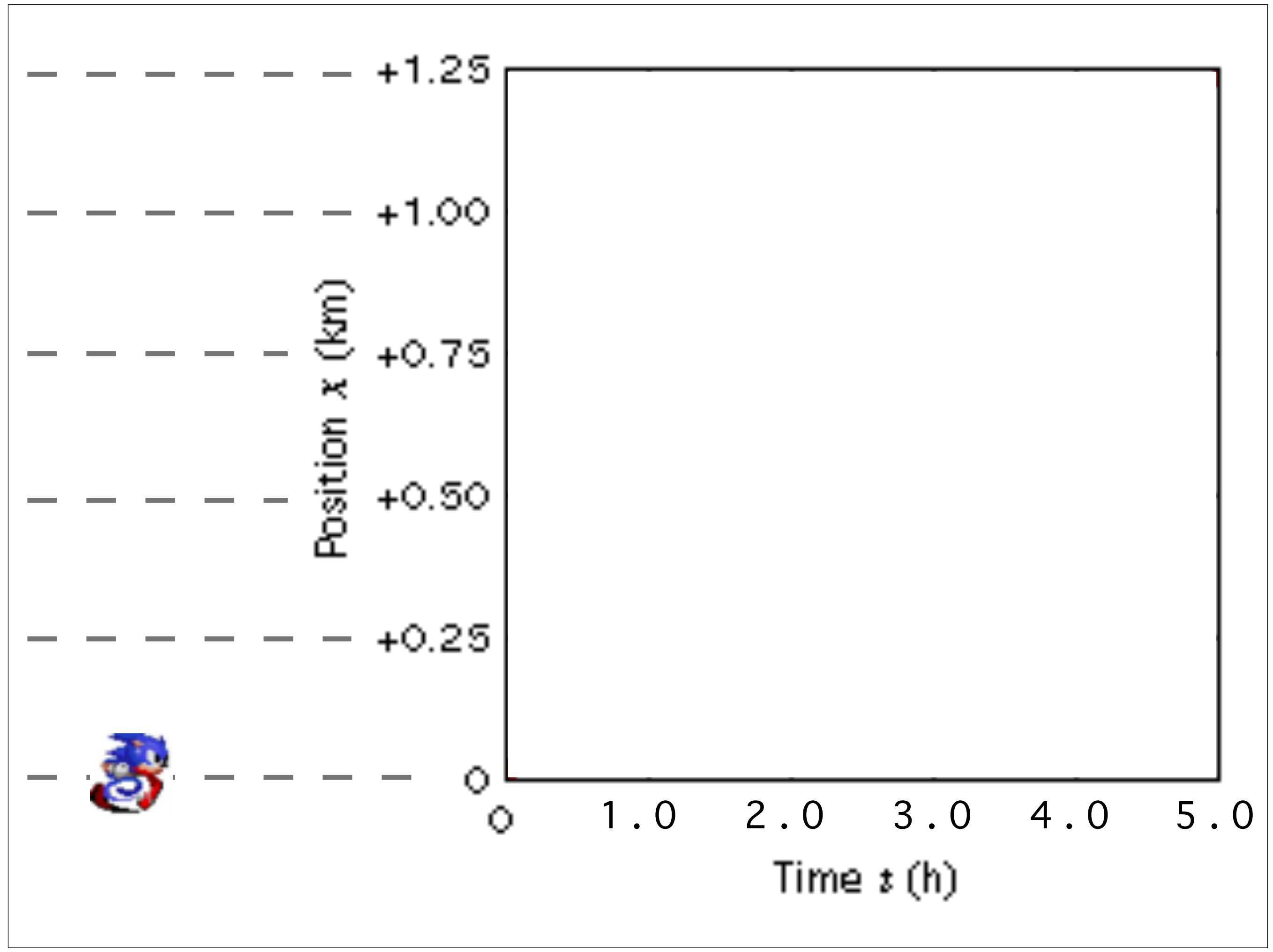
Life is in infinite motion; at the same time it is motionless.

-Debasish Mridha

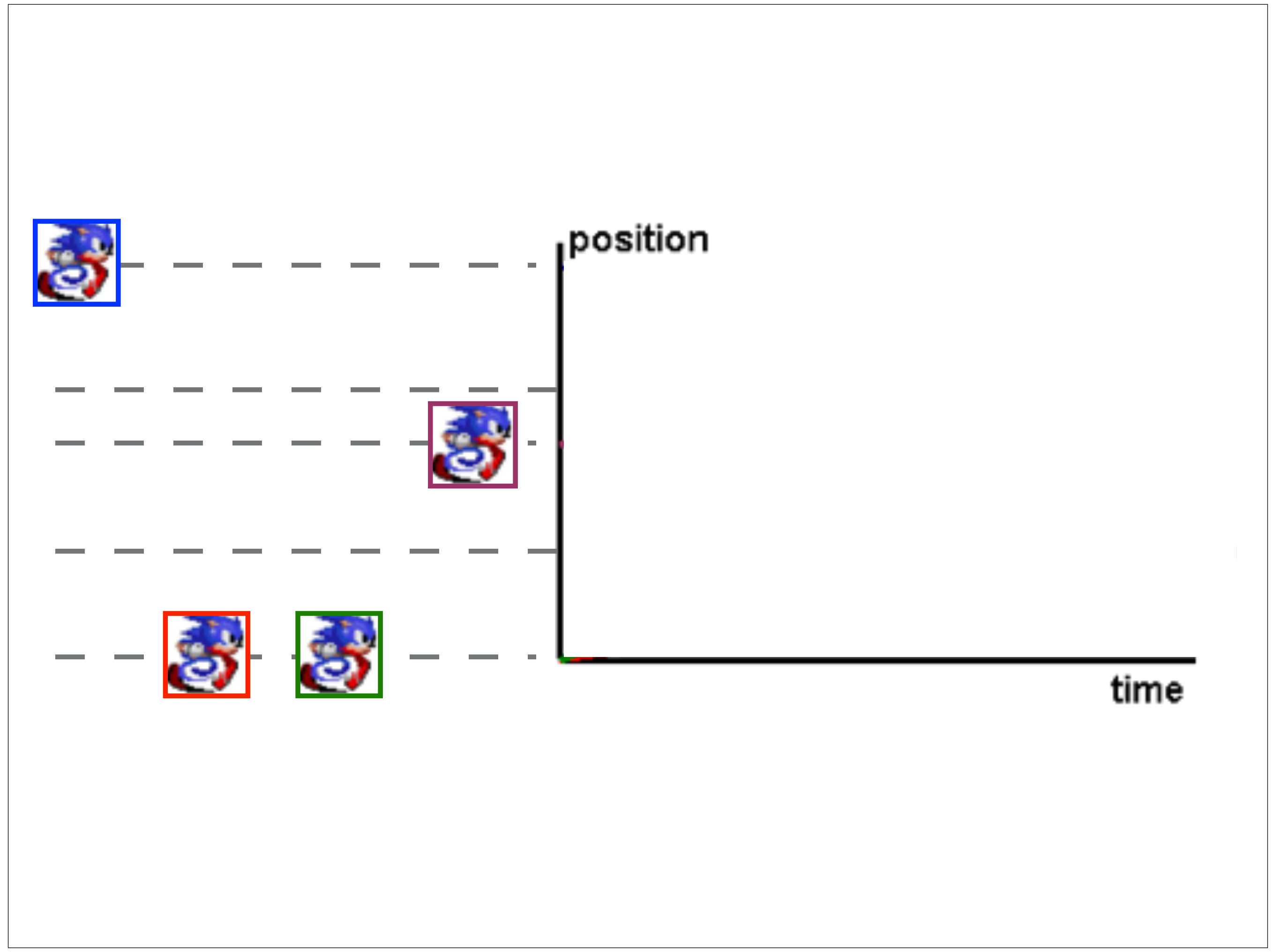
FRAME OF REFERENCE



25
20
15
10
5
0
Position (m)
0 1 2 3 4 5 6 7 8 9 10
Time (s)



Position x (km)
+1.25
+1.00
+0.75
+0.50
+0.25
0
0
1.0
2.0
3.0
4.0
5.0
Time t (h)

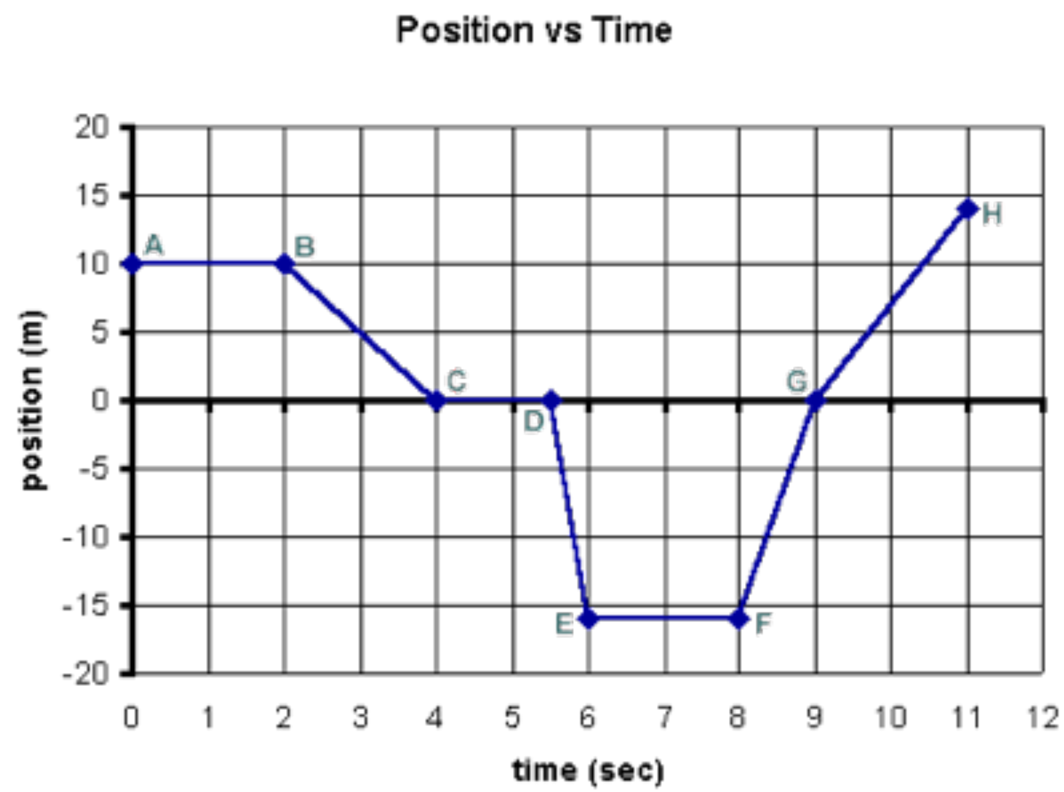


- What can you infer from the graphs? How does the motion of the Sonics compare?

$$v = \frac{dx}{dt}$$

velocity *= rate at which* ***position*** *changes with* ***time***

WHAT ARE THE VELOCITIES REPRESENTED BELOW?

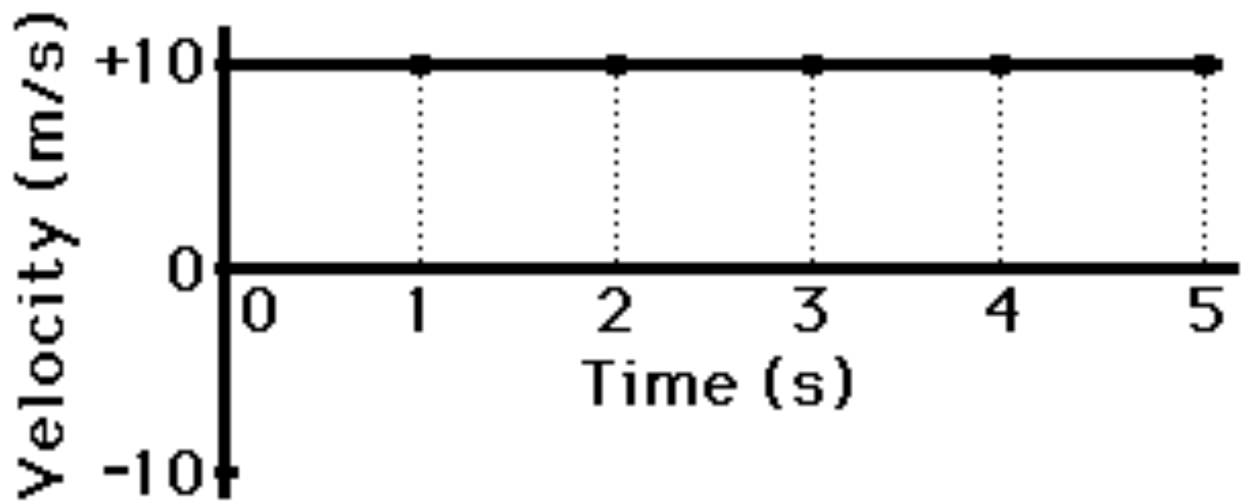


- v_{AB} = 0 m/s, v_{BC} = -5 m/s, v_{CD} = 0 m/s, v_{DE} = -32 m/s, v_{EF} = 0 m/s, v_{FG} = 16 m/s, v_{GH} = 7 m/s

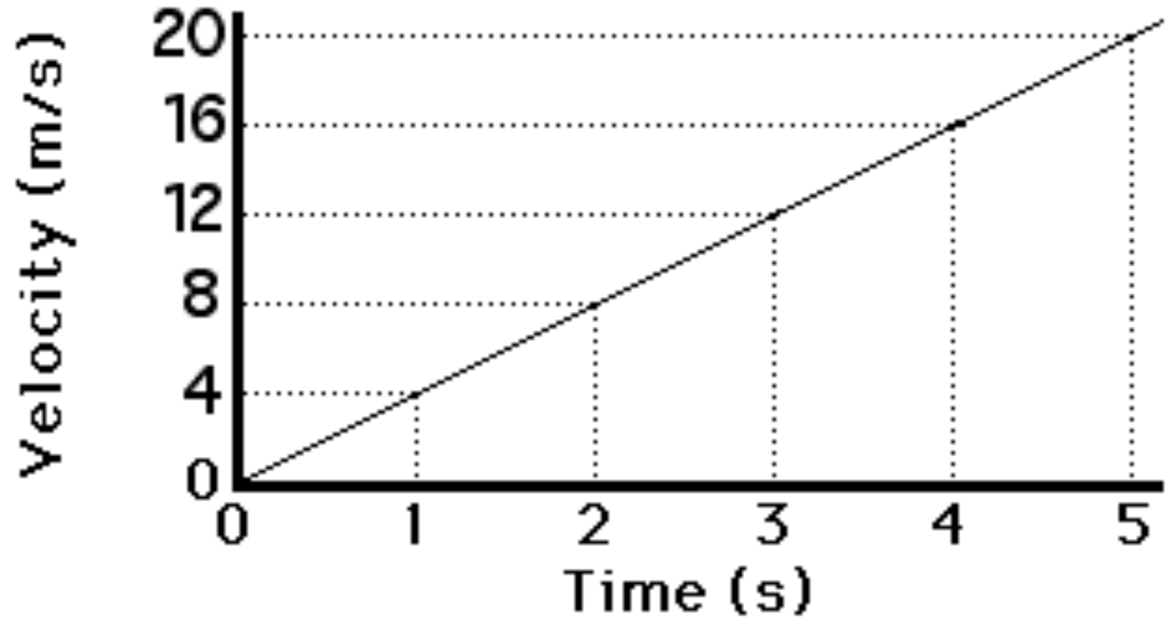
SCENE I: WHERE ARE YOU?

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

HOW FAR HAVE YOU GONE?



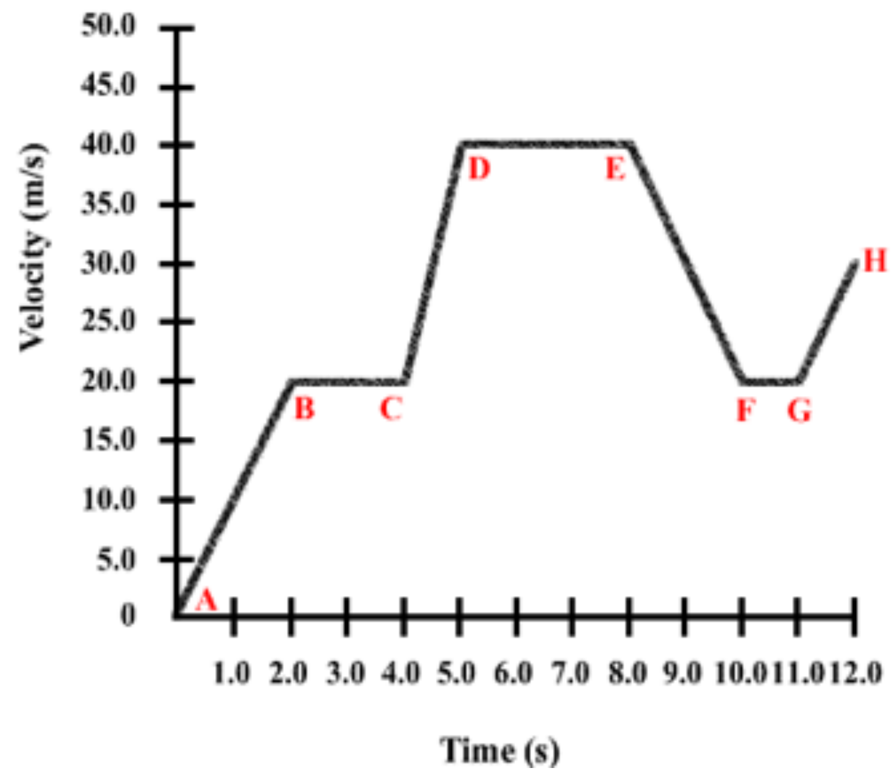
HOW FAR HAVE YOU GONE?



$$\Delta x = \int v \, dt$$

change in ***position*** *=* ***velocity*** *integrated over* ***time***

HOW FAR HAVE YOU TRAVELED?

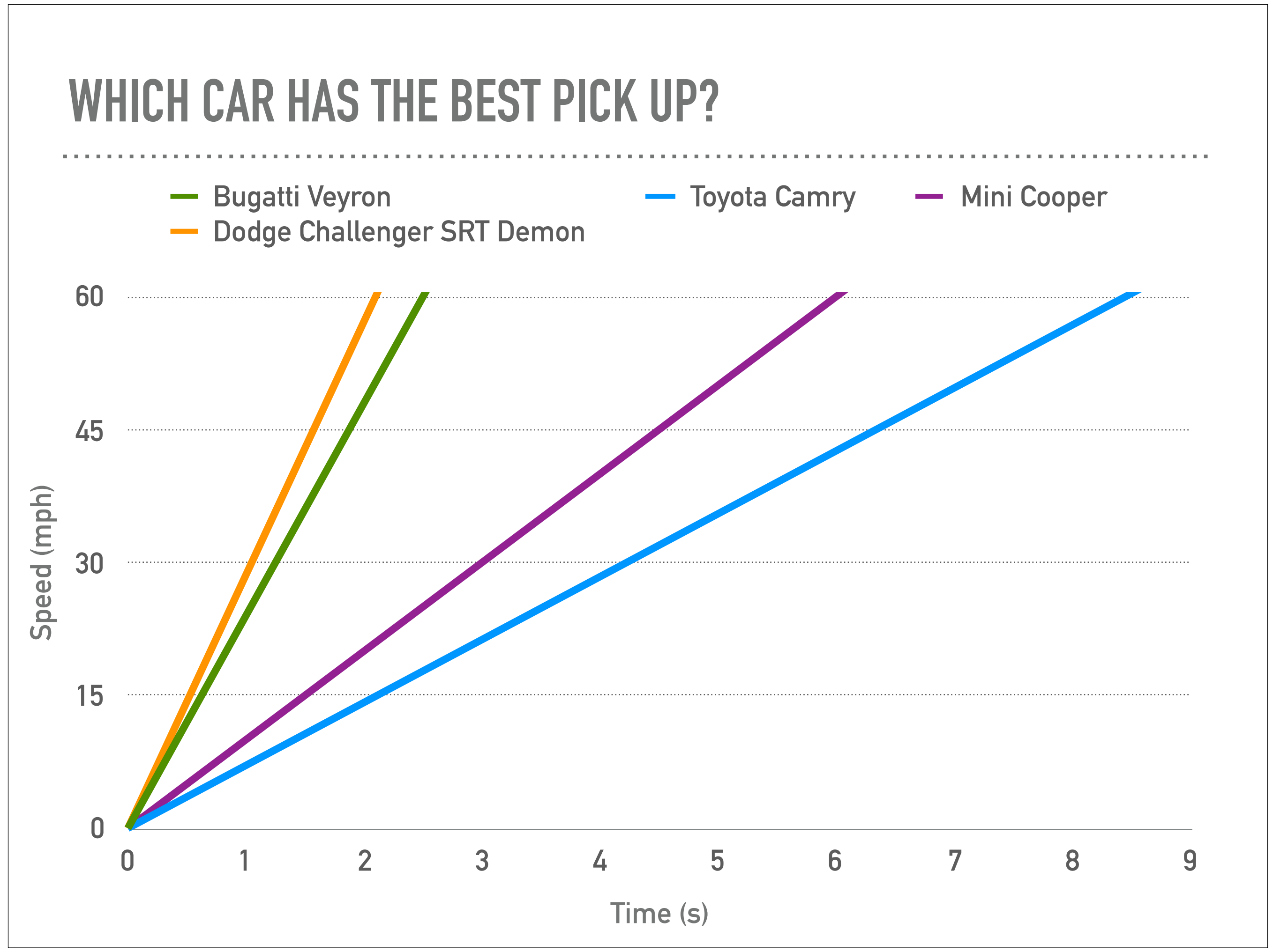


- Δx_{AB} = 20 m, Δx_{BC} = 40 m, Δx_{CD} = 30 m, Δx_{DE} = 120 m, Δx_{EF} = 60 m, Δx_{FG} = 20 m, Δx_{GH} = 25 m
- Δx_{total} = 315 m

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?

IS THAT TRUE?


WHICH CAR HAS THE BEST PICK UP?
Bugatti Veyron
Toyota Camry
Mini Cooper
Dodge Challenger SRT Demon
Speed (mph)
60
45
30
15
0
0
1
2
3
4
5
6
7
8
9
Time (s)

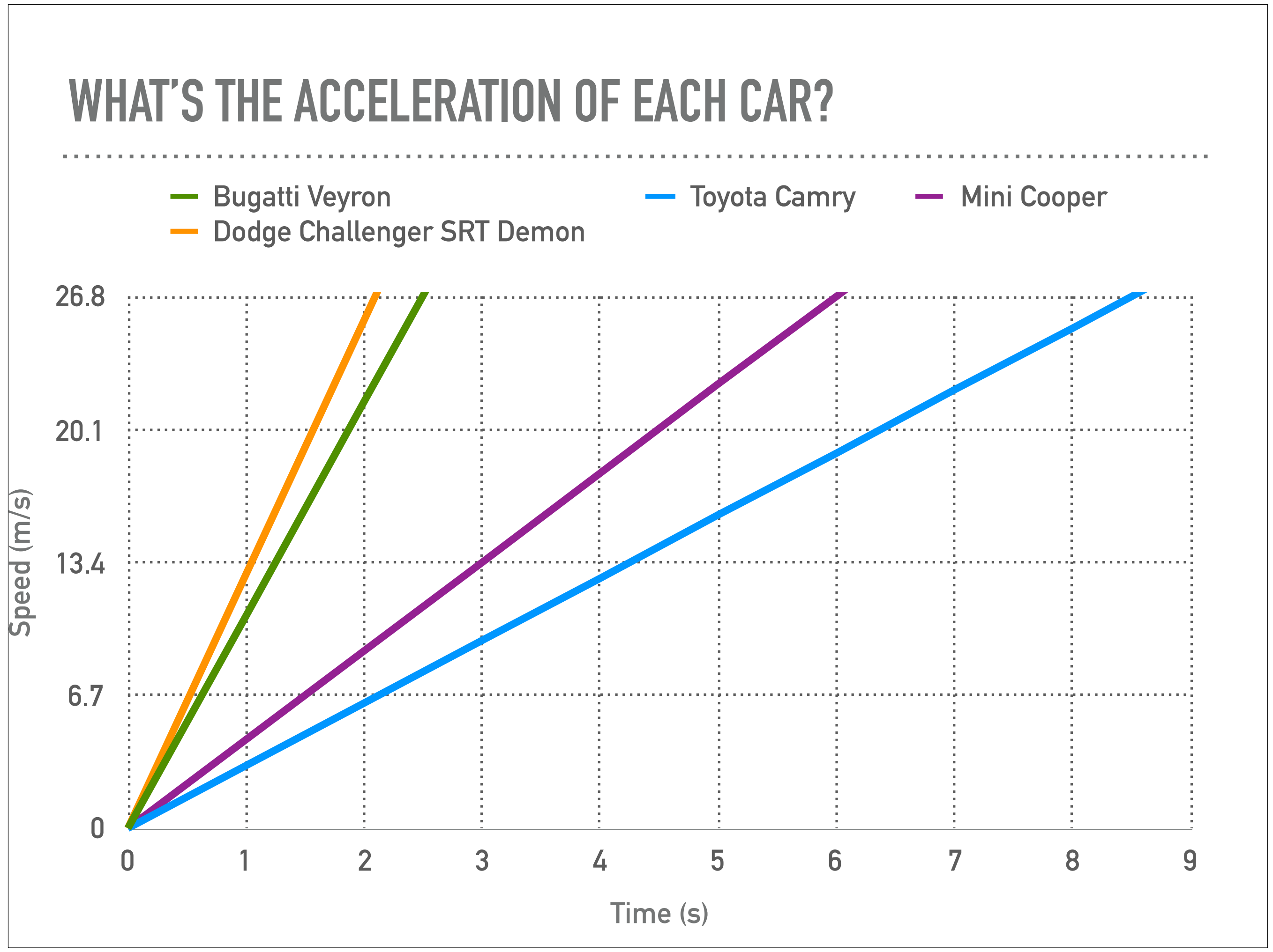
WHICH CAR HAS THE BEST PICK UP?

	Time (s)	Speed (mph)
Bugatti Veyron	2.5	60
Toyota Camry	8.5	60
Mini Cooper	6.0	60
Dodge Challenger SRT Demon	2.1	60

Skip this slide

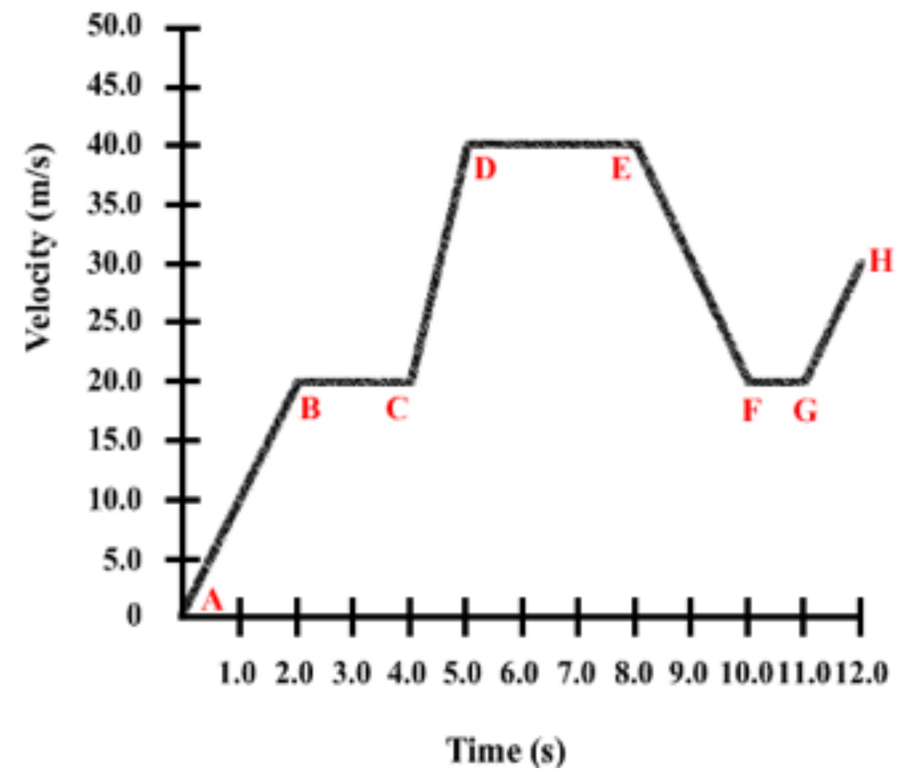
$$a = \frac{dv}{dt}$$

acceleration *= rate at which* ***velocity*** *changes with* ***time***



➤ Answers: a_{DC} = 12.8 m/s , a_{BV} = 10.7 m/s , a_{MC} = 4.47 m/s , a_{TC} = 3.15 m/s

WHAT ARE THE ACCELERATIONS?

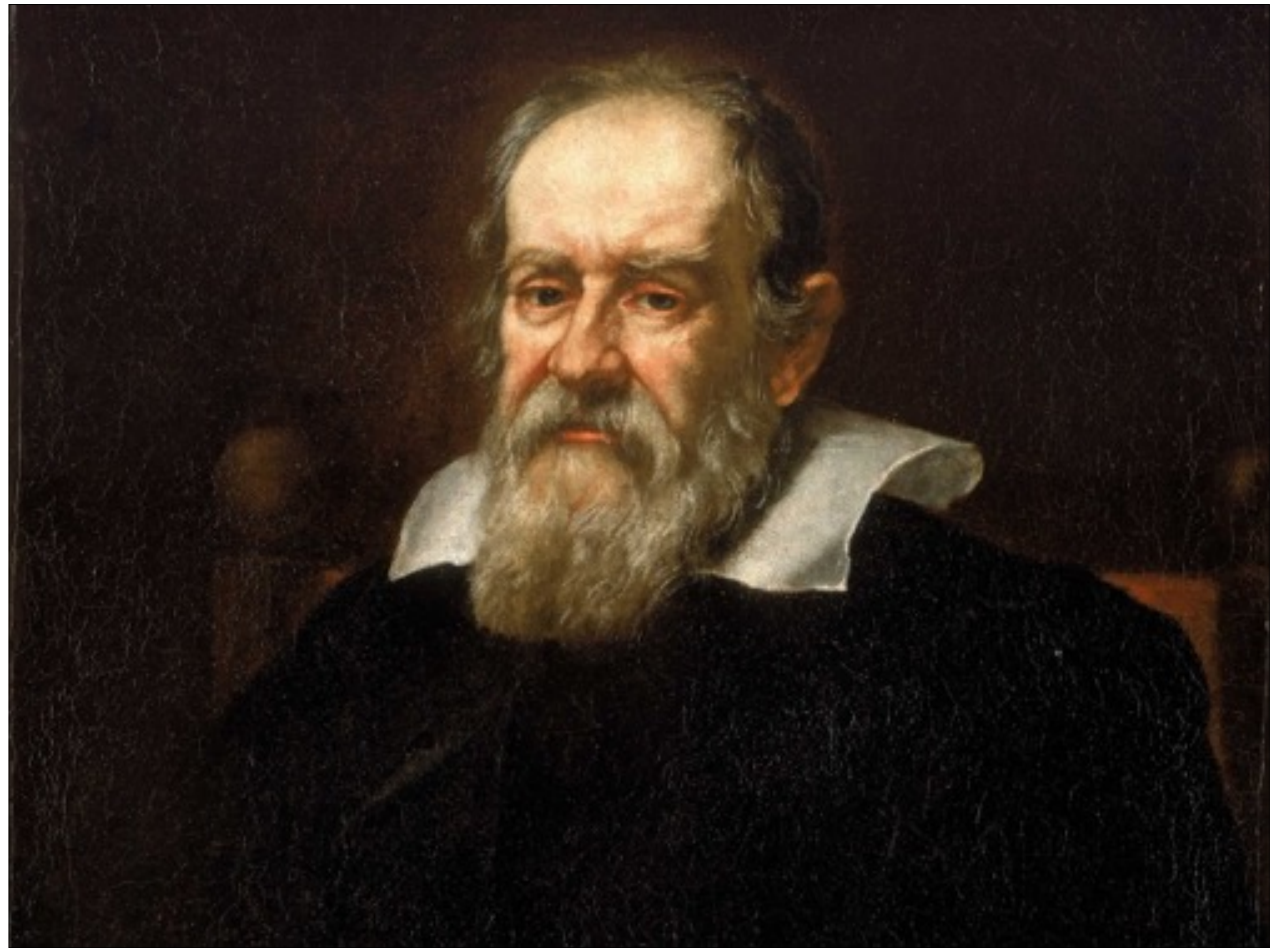


- a_{AB} = 10 m/s , a_{BC} = 0 m/s , a_{CD} = 20 m/s , a_{DE} = 0 m/s , a_{EF} = -10 m/s , a_{FG} = 0 m/s , a_{GH} = 10 m/s

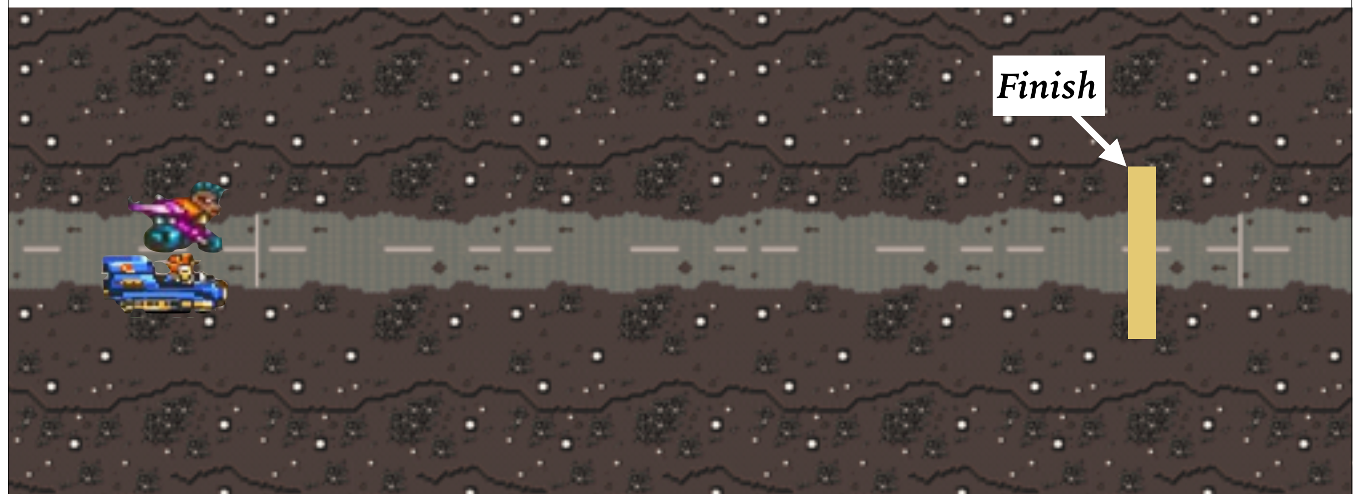

SPEEDHUNTERS


ONEGIF.COM

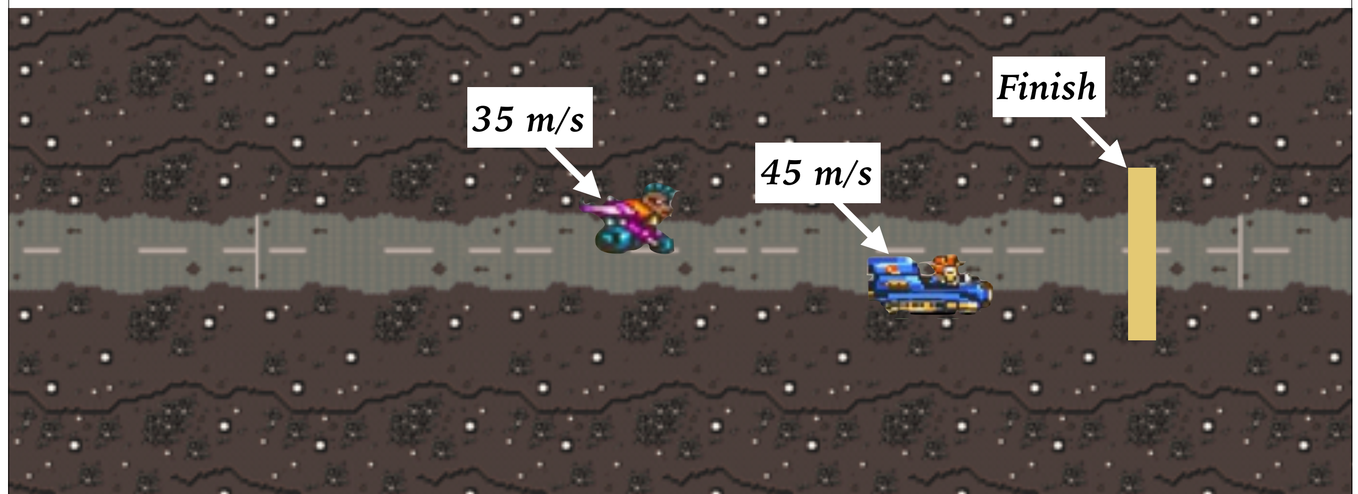
GALILEAN RELATIVITY



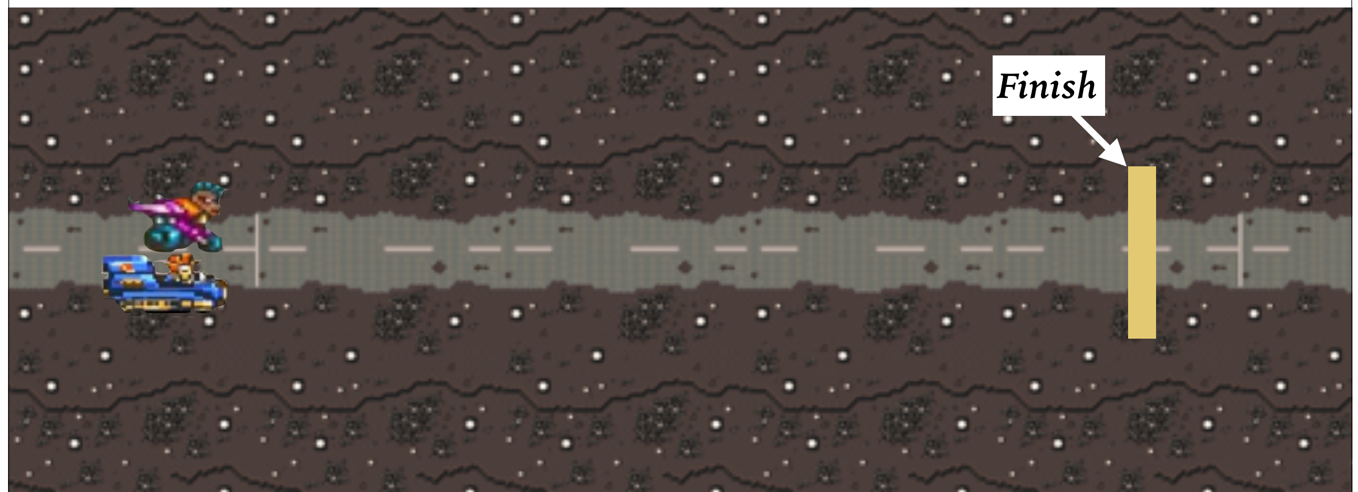
GALILEAN RELATIVITY



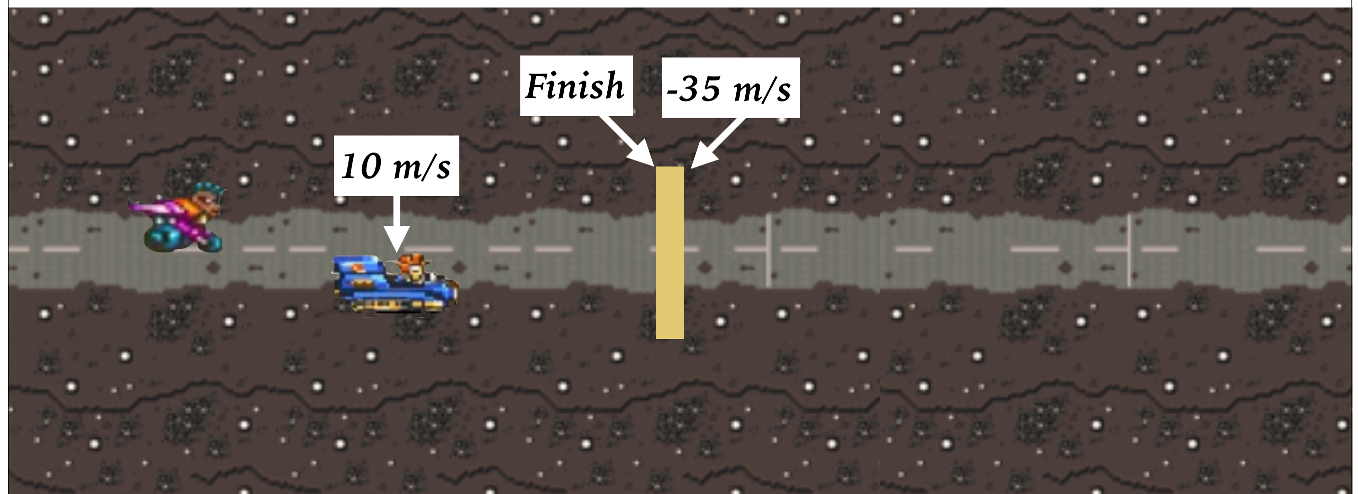
GALILEAN RELATIVITY



GALILEAN RELATIVITY



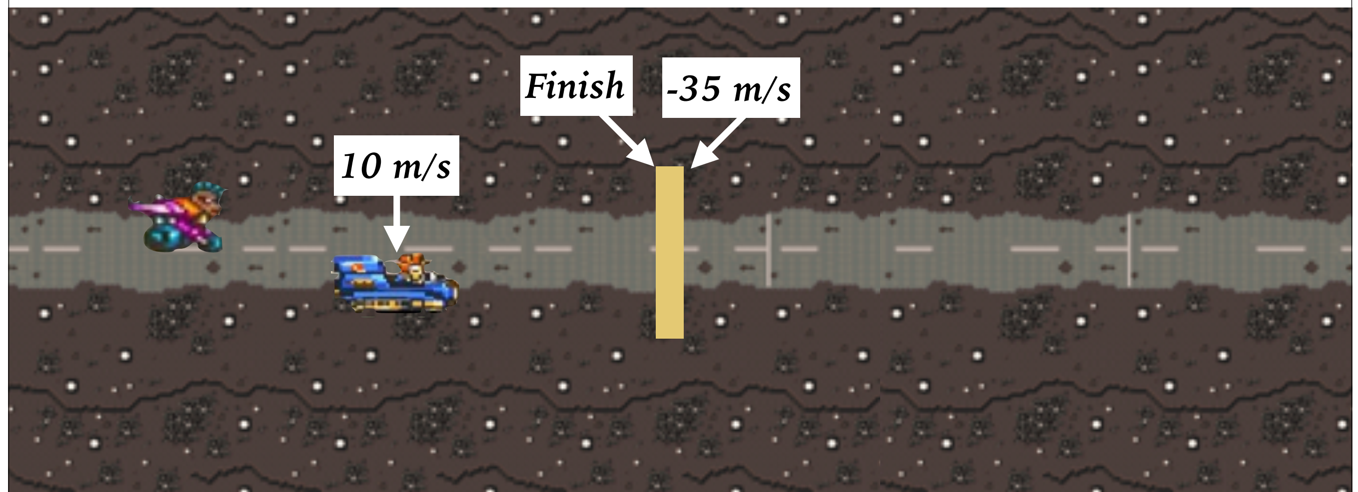
GALILEAN RELATIVITY

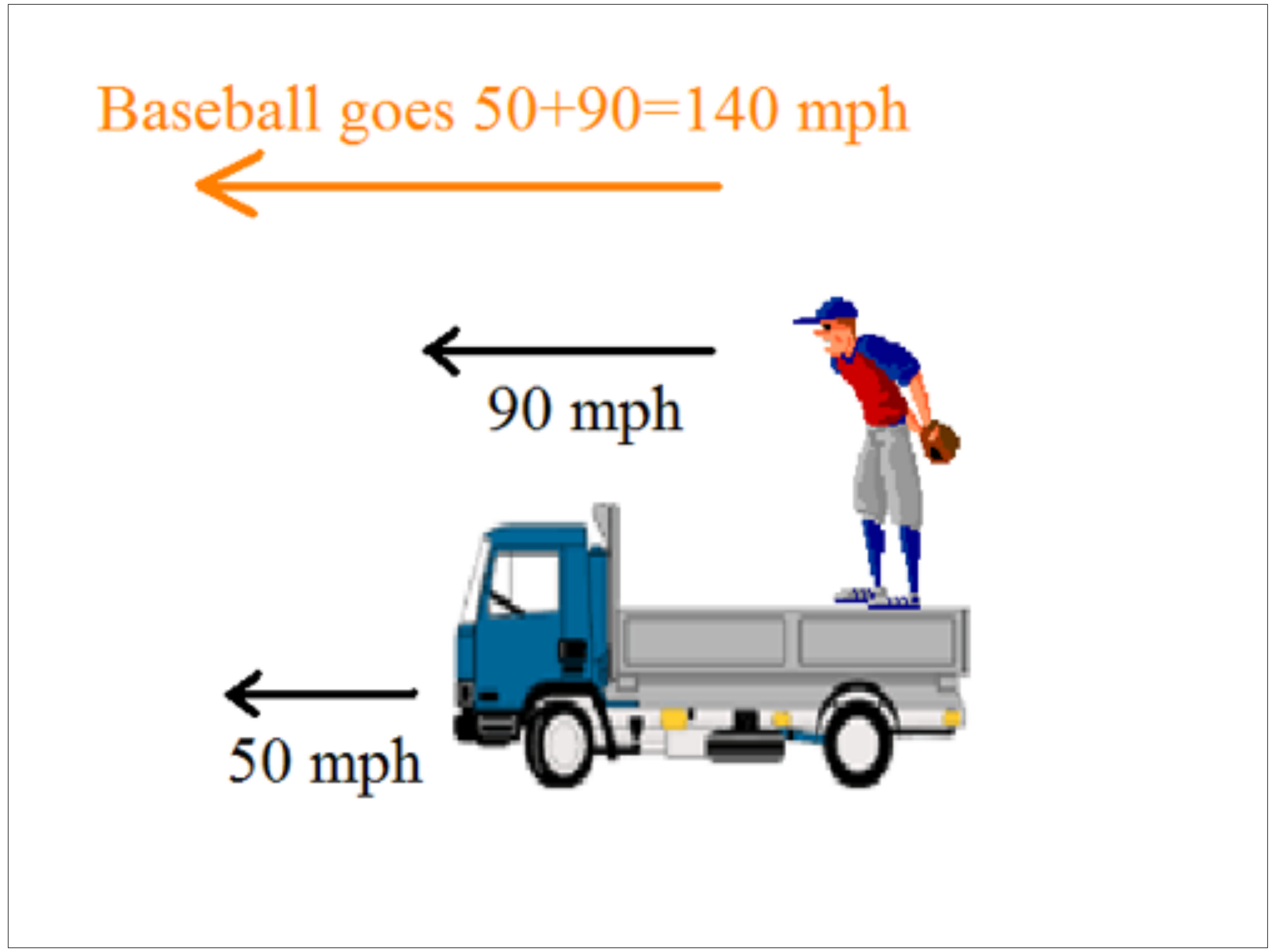


“

In physics, a negative sign indicates direction

GALILEAN RELATIVITY




Baseball goes 50+90=140 mph
90 mph
50 mph

SANITY CHECK

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

SCENE II: WHERE ARE YOU GOING?

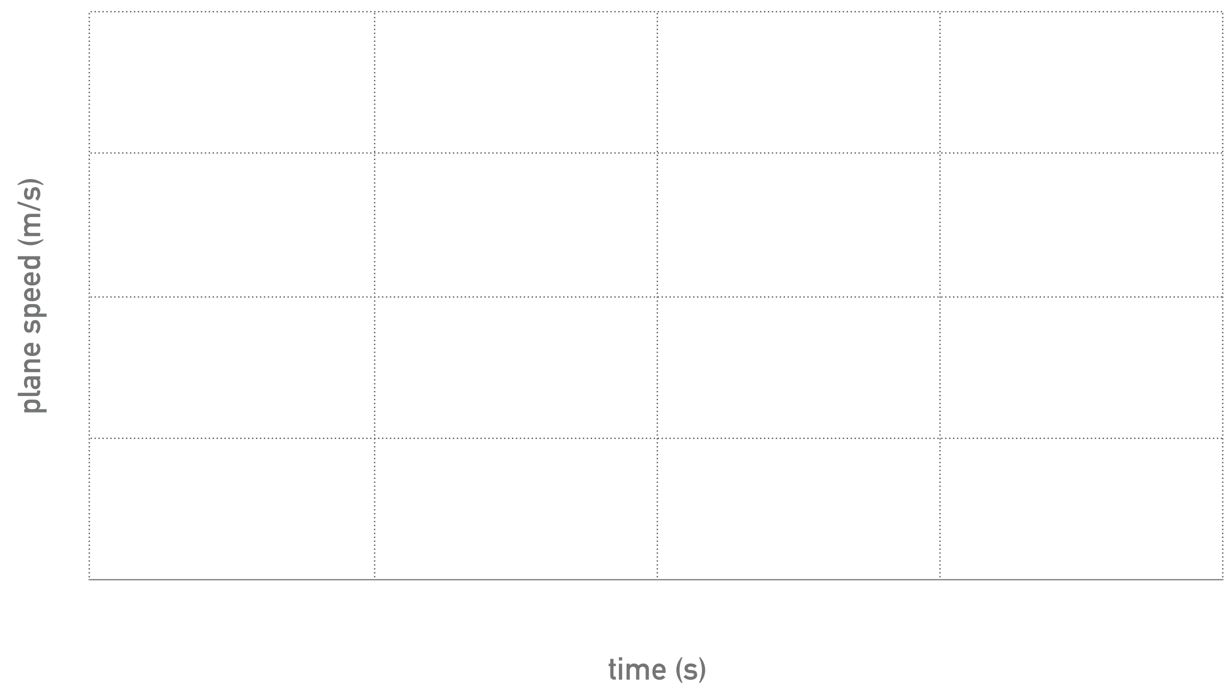
Kinematics — The Study of How Things Move

Florence Griffith-Joyner, USA, World Record Women’s 200m at 21.34 s

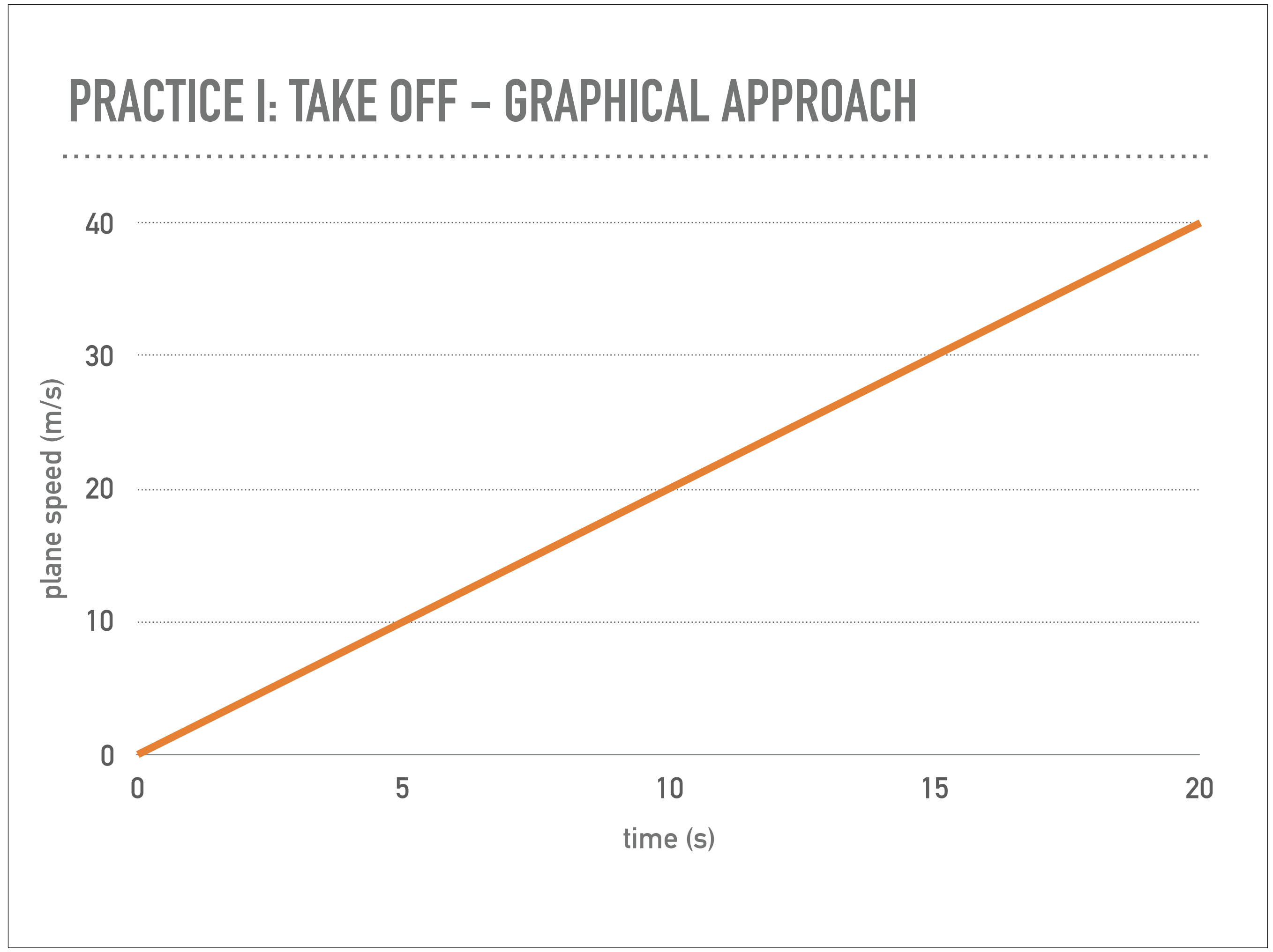
PRACTICE I: TAKE OFF

- 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 27.8 m/s (100 km/h) and can accelerate at 2.00 m/s^2. If the runway is 90-m-long, can this plane speed to take off?

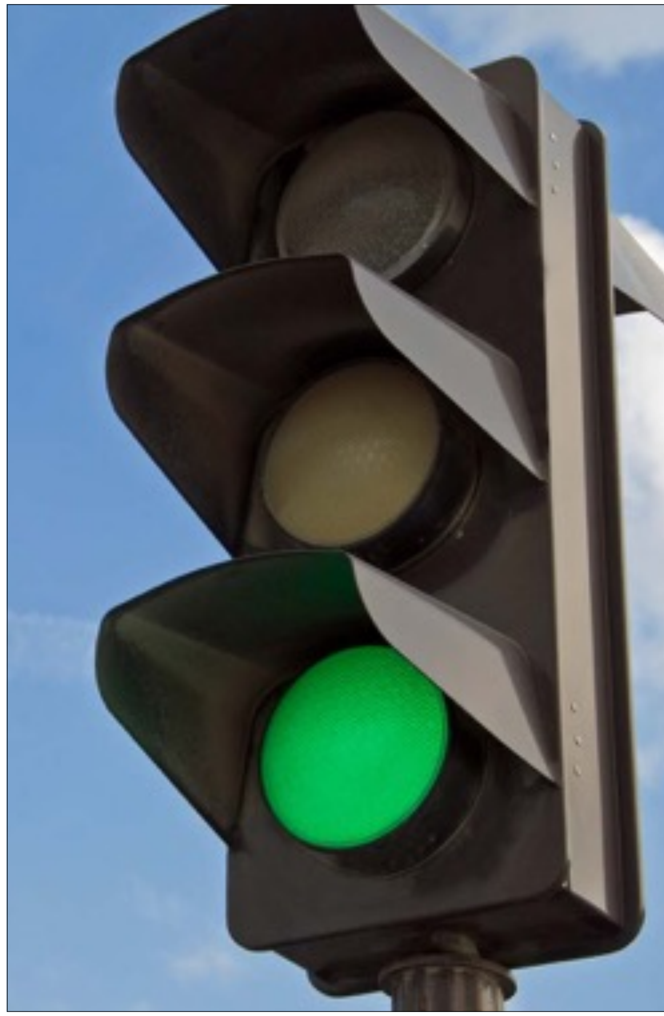
PRACTICE I: TAKE OFF – ESTIMATION



- Use graph to help derive $\Delta x = v\ /2a$ [$\frac{1}{2}bh = \frac{1}{2}(v/a)(v)$]



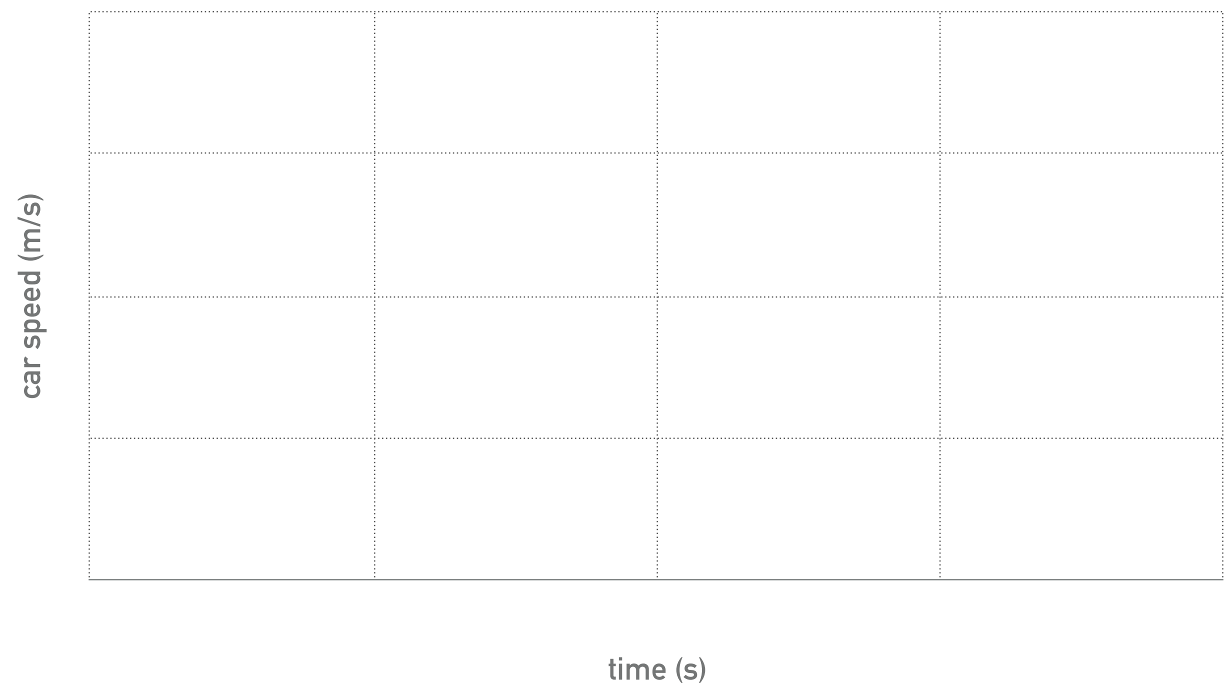
➤ Solve using graph values



PRACTICE II: GREEN MEANS GO

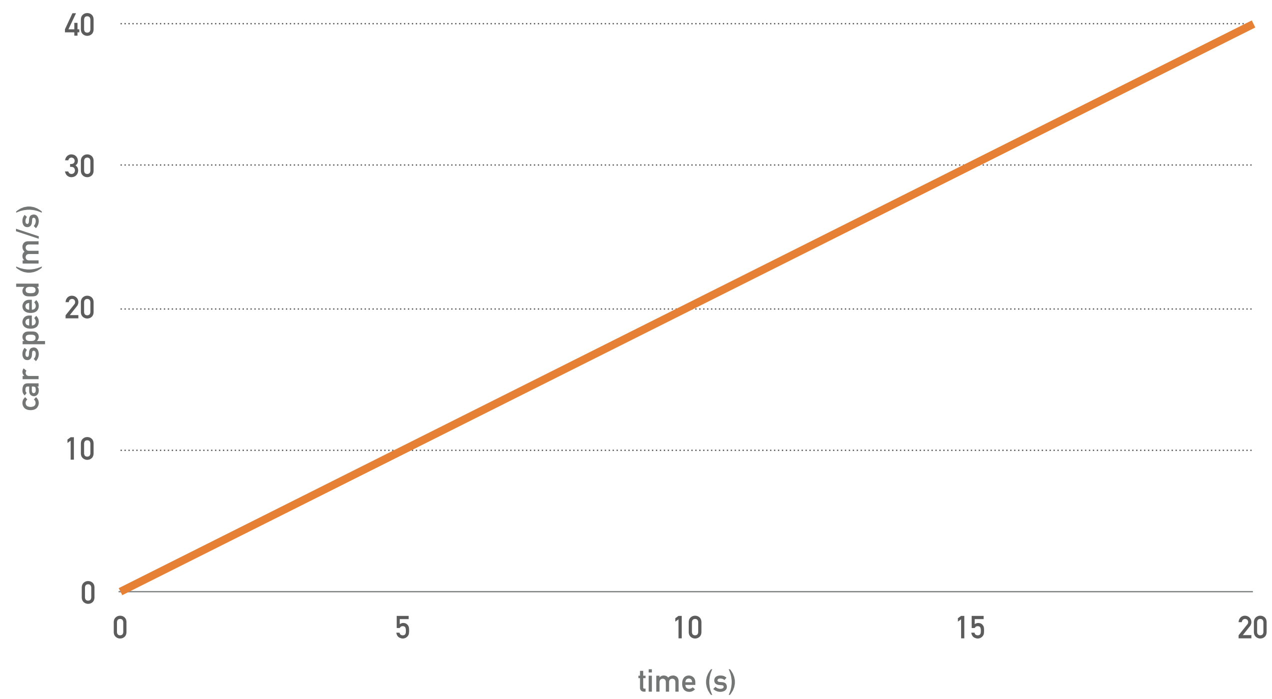
- How long does it take a car to cross a 33.0-m-wide intersection after the light turns green if it accelerates from rest at a constant 2.23 m/s^2?

PRACTICE II: GREEN MEANS GO – ESTIMATION



- Use graph to help derive $\Delta x = \frac{1}{2}a\Delta t$ [$\frac{1}{2}bh = \frac{1}{2}(\Delta t)(a\Delta t)$]

PRACTICE II: GREEN MEANS GO – GRAPHICAL APPROACH

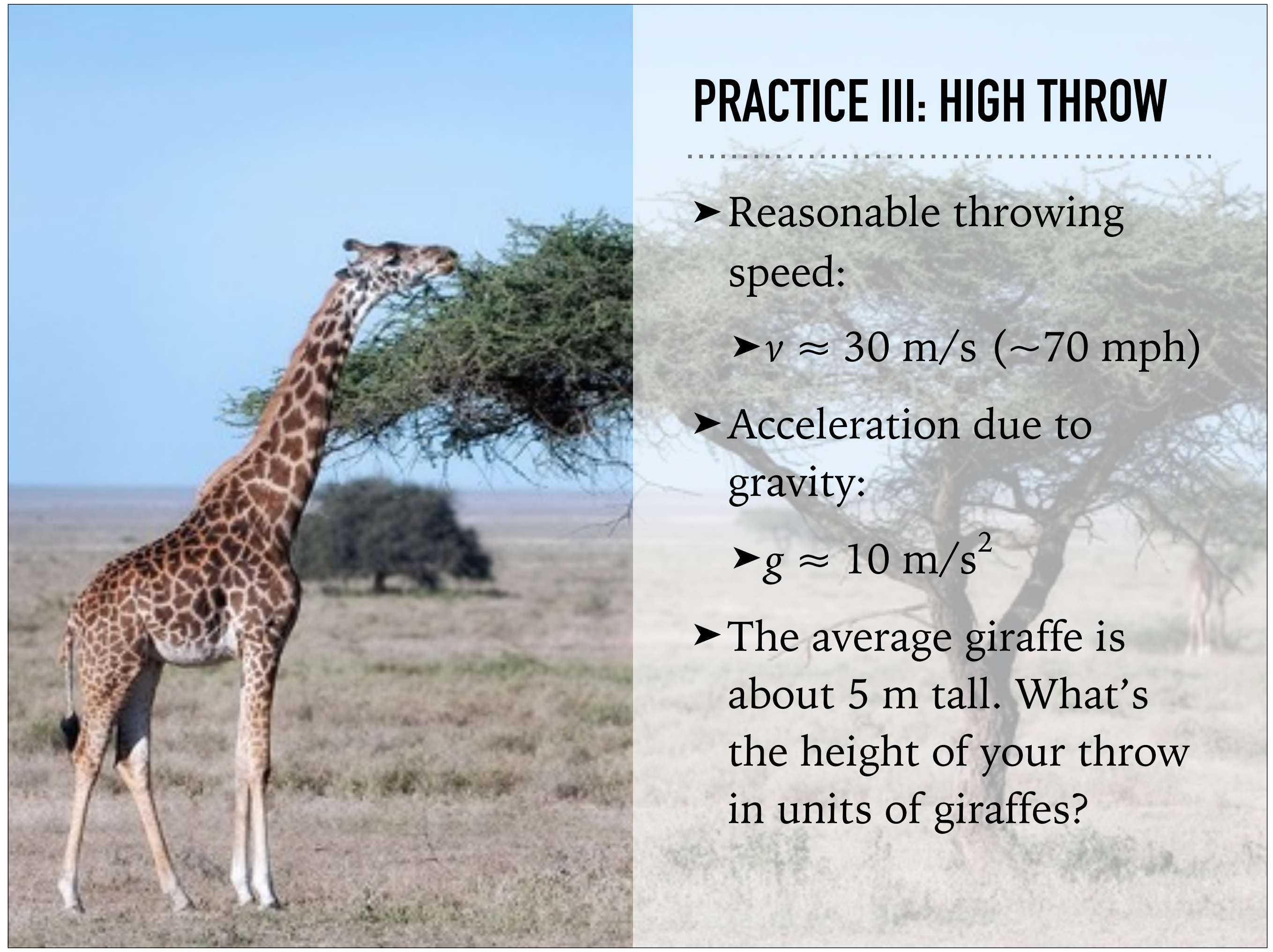


➤ Solve using graph values

PRACTICE III: HIGH THROW

- How high can a human throw something?

- What do we need to know to answer this problem? (throwing speed & *g*)



- Answer: ~45 m
- But with *air resistance* take off ~50%

PRACTICE III: HIGH THROW

- Aroldis Chapman set the world record with a 105 mph fastball
- How high (in giraffes) could he hypothetically launch a baseball?

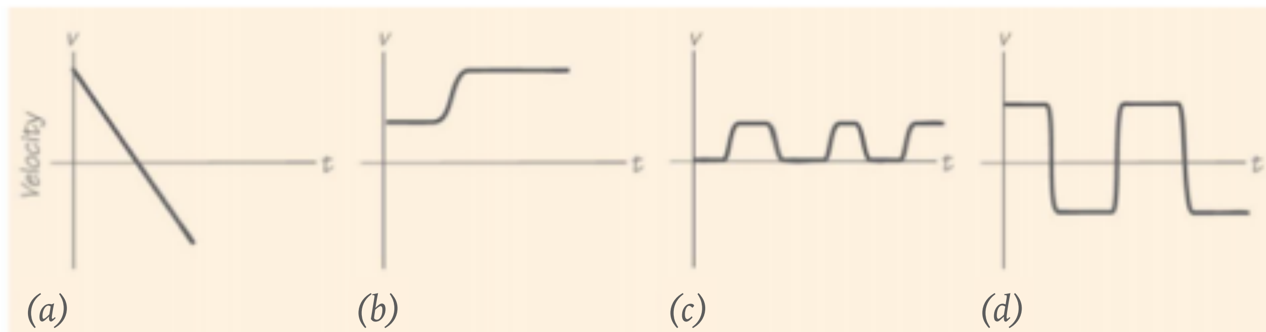
- 105 mph = 47 m/s
- Answer: ~100 m or 50-60 m w/ air resistance

YOUR TURN!

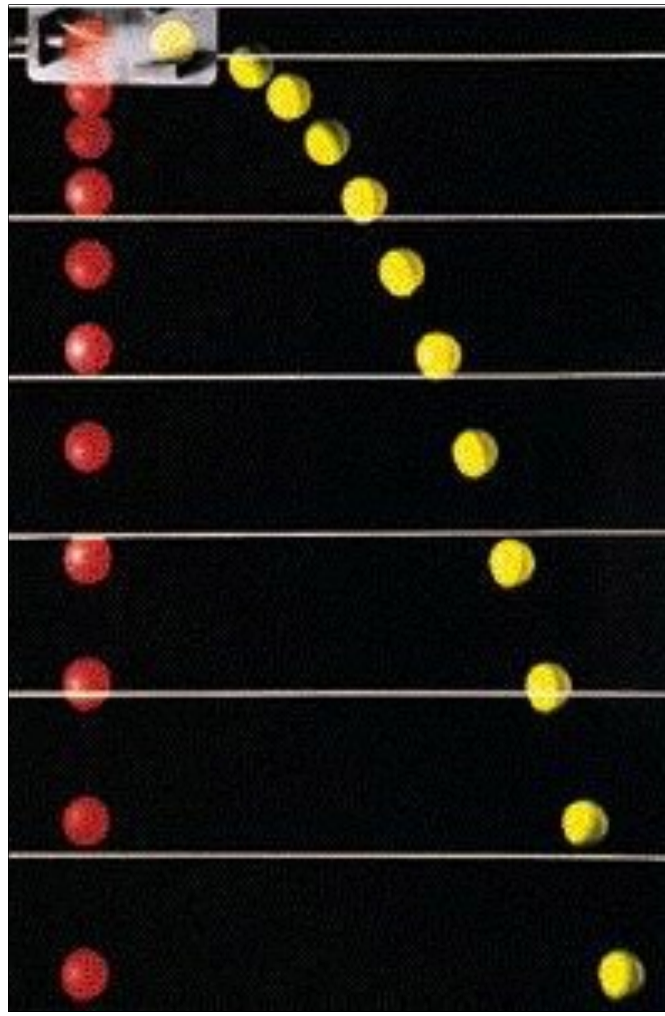
- Think of a problem that kinematics would be helpful for solving and create a word problem around it
  - What values could you easily measure? Which would you need to infer or deduce?
- Get out a new sheet of paper
  - On one side, write the problem
  - On the back side, write the answer key. Be sure to explain the steps!

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



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



PROJECTILE MOTION

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

- Give demo before
- Do stomp rocket demo after
  - Measure time and range, estimate distance (theta = 0º, 15º, 30º, 45º, 60º, 75º, 90º)

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

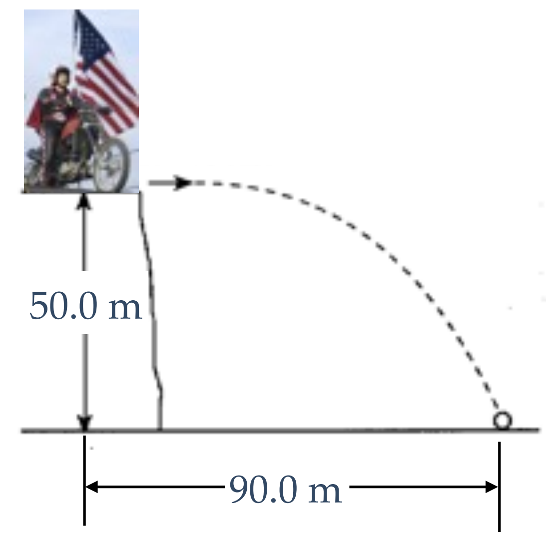
  B. in front of you

  C. back in your lap

Answer: C

PRACTICE IV: STUNTIN' ON EVERYBODY

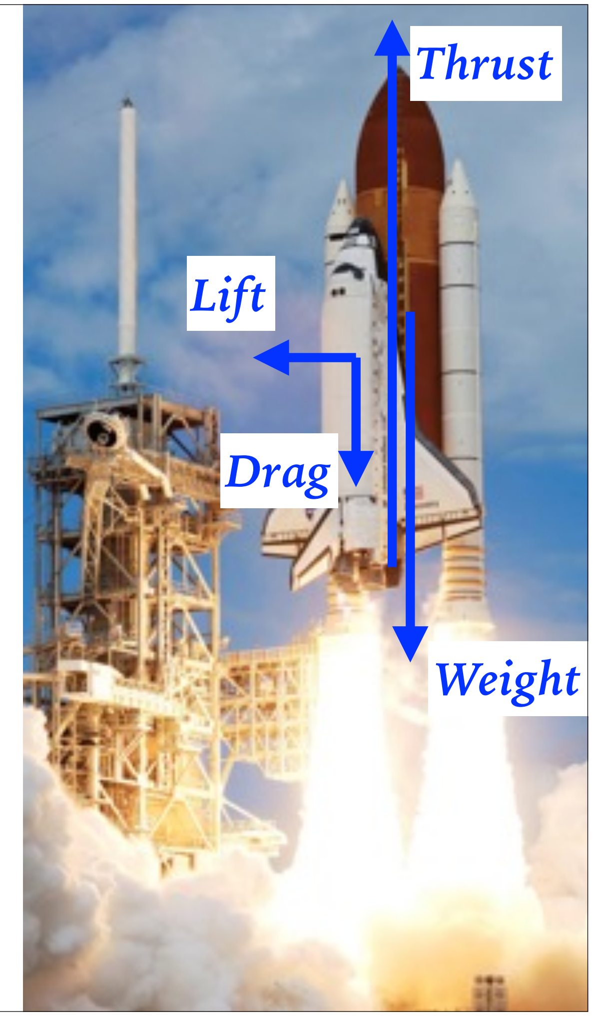
- Rod Kimble, stuntman, drives his motorcycle off a 50.0-m-high cliff to raise money for his stepdad's heart surgery. On his first run, Rod has just over 3 seconds of air time before landing 90 m from the base of the cliff.
- If he tries again driving twice as fast,
  - a) about how far from the base of the cliff can we expect him to land?
  - b) about how much time can we expect him to be in the air?



- Answers: (a) ~180 m, (b) 3 sec.

SCENE III: HOW ARE YOU GETTING THERE?

Dynamics — The Study of Why Things Move



- Discussion on reading including Aristotle's view on objects in motion, Galileo's conclusion based on limiting cases, and Newton's Laws

> An object continues in its state of rest or of uniform speed in a straight line unless acted on by an external, unbalanced force
>
> *The First Law of Motion*

THE LAW OF INERTIA

Inertia — a body’s resistance to changes in it’s 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*

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

- Definition of force

SCENE III: HOW ARE YOU GETTING THERE?

- Measured in *newtons* (N)
- 1 N = 1 kg•m/s^2

"For every action there is an equal and opposite reaction

The Third Law of Motion

(RE)ACTION

- Identify the action-reaction pairs
  1. Baseball in freefall
  2. A baseball bat knocks a ball into left field
  3. Enclosed air particles push balloon wall outwards
  4. Rocket launches into the air
  5. Usain Bolt runs around the track
- Reactions:
  1. Baseball pulls Earth up
  2. The ball pushes the bat back and to the right
  3. Balloon wall pushes air inward
  4. Rocket fuel pushes rocket up
  5. Ground pushes Usain forward

NEWTON'S LAWS OF MOTION

I. An object continues in its state of rest or of uniform speed in a straight line 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

PRACTICE V: RICK & MORTY

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

- $F_{net} \approx 5000$ N

PRACTICE VI: RICK & MORTY, 2

- Rick and Morty escaped the Gazorpazorps and pull into the garage. The 1000 kg spaceship is brought to rest in the garage from a speed of 100 km/h within a distance of 55 m.

a) What's the net acceleration?

b) What net force is required?

c) What if they needed to stop in half the distance?

Answers:

a) $a \approx 8\ \text{m/s}^2$

b) $F_{net} \approx 8000\ \text{N}$

c) $a \approx 16\ \text{m/s}^2$ & $F_{net} \approx 16{,}000\ \text{N}$

WEIGHT = FORCE OF GRAVITY

PRACTICE VII: ALIEN ABDUCTION

- Raphaldo (m = 71.0 kg) sits in his room minding his own business

  a) What is Raphaldo's weight?

- 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's finds his weight is only 263 N on Mars!

  b) What is the acceleration due to gravity on Mars?

- Answers:

a) $F_g \approx 700$ N

b) $a_g \approx 4$ m/s^2

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?

- Gravity pulls the Earth up towards the object

Normal Force — contact force

In physics & math, *normal* means *perpendicular*

- Bathroom scales actually measure normal force

FRICTION

FRICTION

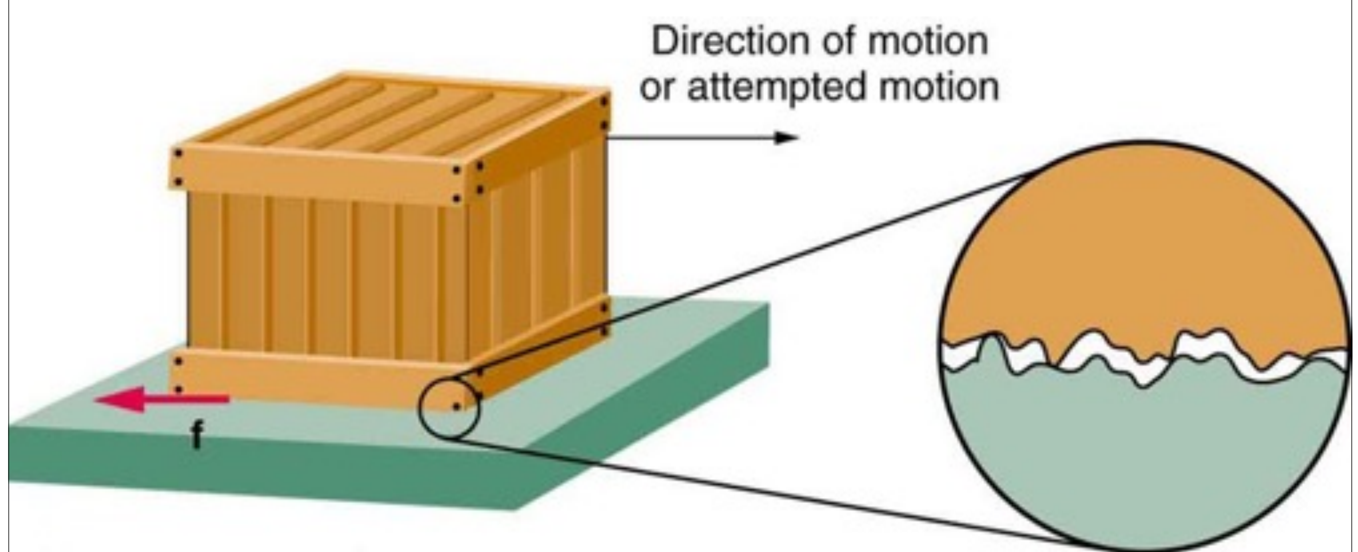
kinetic

static

rolling

fluid

Friction always opposes motion


Direction of motion
or attempted motion
f

FRICTION

- What factors, apart from the relative roughness of the surfaces, affect the force of friction?

Surprise! Surface area and speed don’t matter to friction

$$F_{\mathrm{fr}} \propto F_{\mathrm{N}}$$

*the force of **friction** is proportional to the **normal** force*

$$F_{\mathrm{drag}} \propto Av^2$$

drag *forces are proportional to the object's* ***surface area*** *& the* ***square*** *of its* ***velocity***

- Enter pressure
- What are you supposed to do when on thin ice? (flatten against the ground)

PRESSURE

$$p \propto F/A$$

pressure *is equal to the* ***force*** *applied &*
inversely proportional to the ***surface area***

PRESSURE

- Measured in *pascals* (Pa)

- $1\ Pa = 1\ N/m^2 = 1\ kg/m \cdot s^2$

PRESSURE

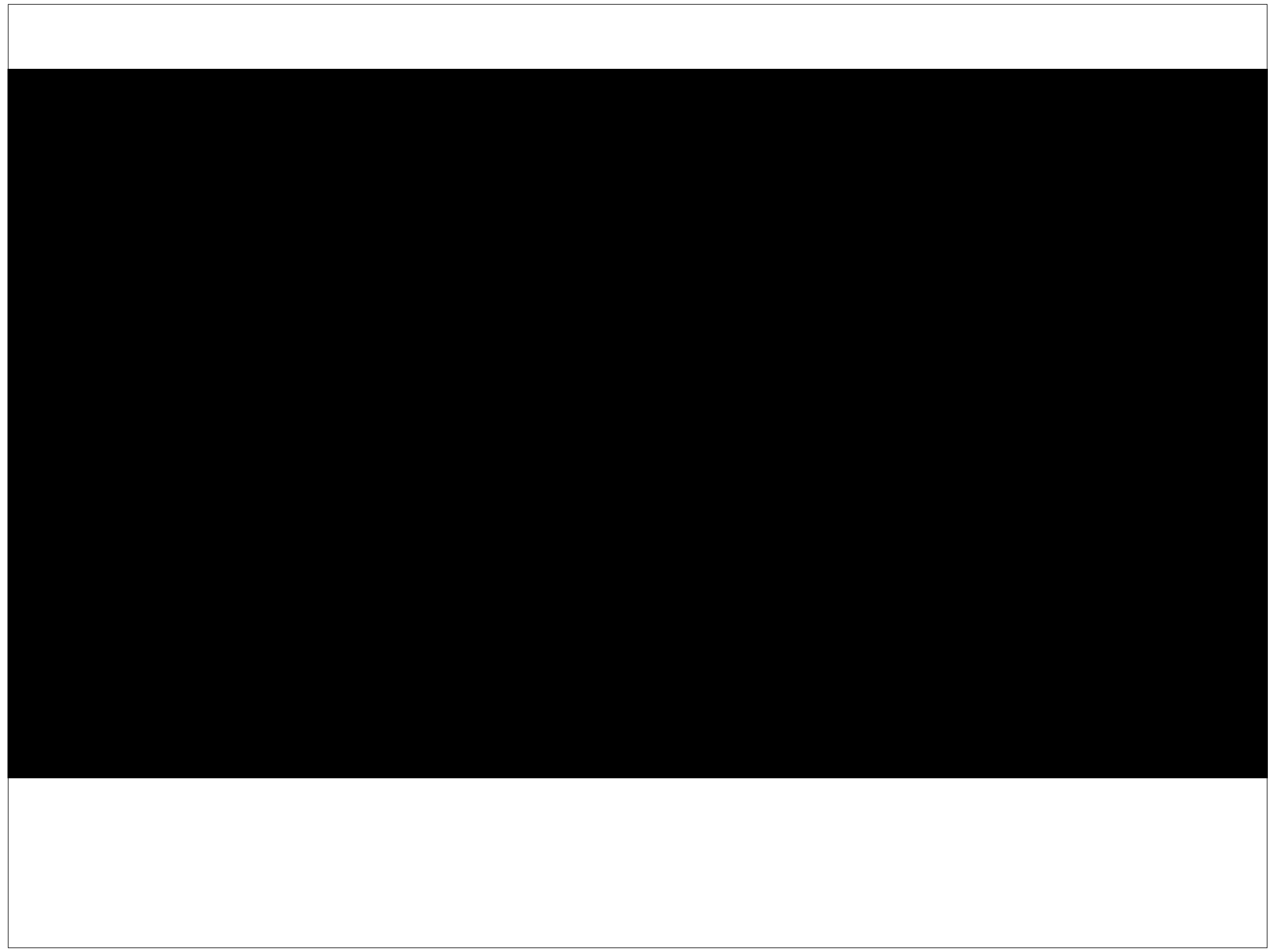
- **1 Pa** ~ a dollar bill resting flat on a surface
- **100,000 Pa** ≈ 1 atm
- **200,000 Pa** ~ standard tire pressure
- **10^{-17} Pa** ~ pressure in outer space in intergalactic voids (lowest pressure ever measured)
- **10^{10} Pa** ~ pressure needed to make diamond

BUOYANCY

$$F_{buoy.} \propto V_{displaced}\,\rho_{fluid}$$

*the **buoyant force** is proportional to the **volume** of the fluid displaced & the **density** of the fluid*

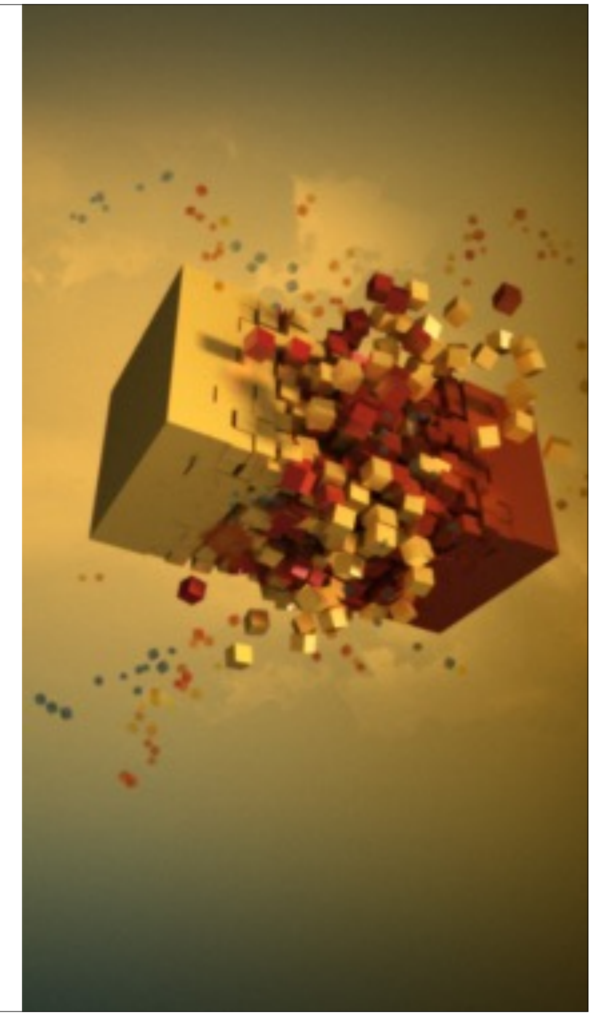
- In full form, the buoyant force is equal to the *weight* of the fluid displaced, but this is a helpful way to think about it



- *Veritasium* Beaker Ball Balance Problem
- https://www.youtube.com/watch?v=QD3hbVG1yxM

SCENE IV: WHAT IF SOMETHING GETS IN THE WAY?

Collisions & Conservation of Momentum



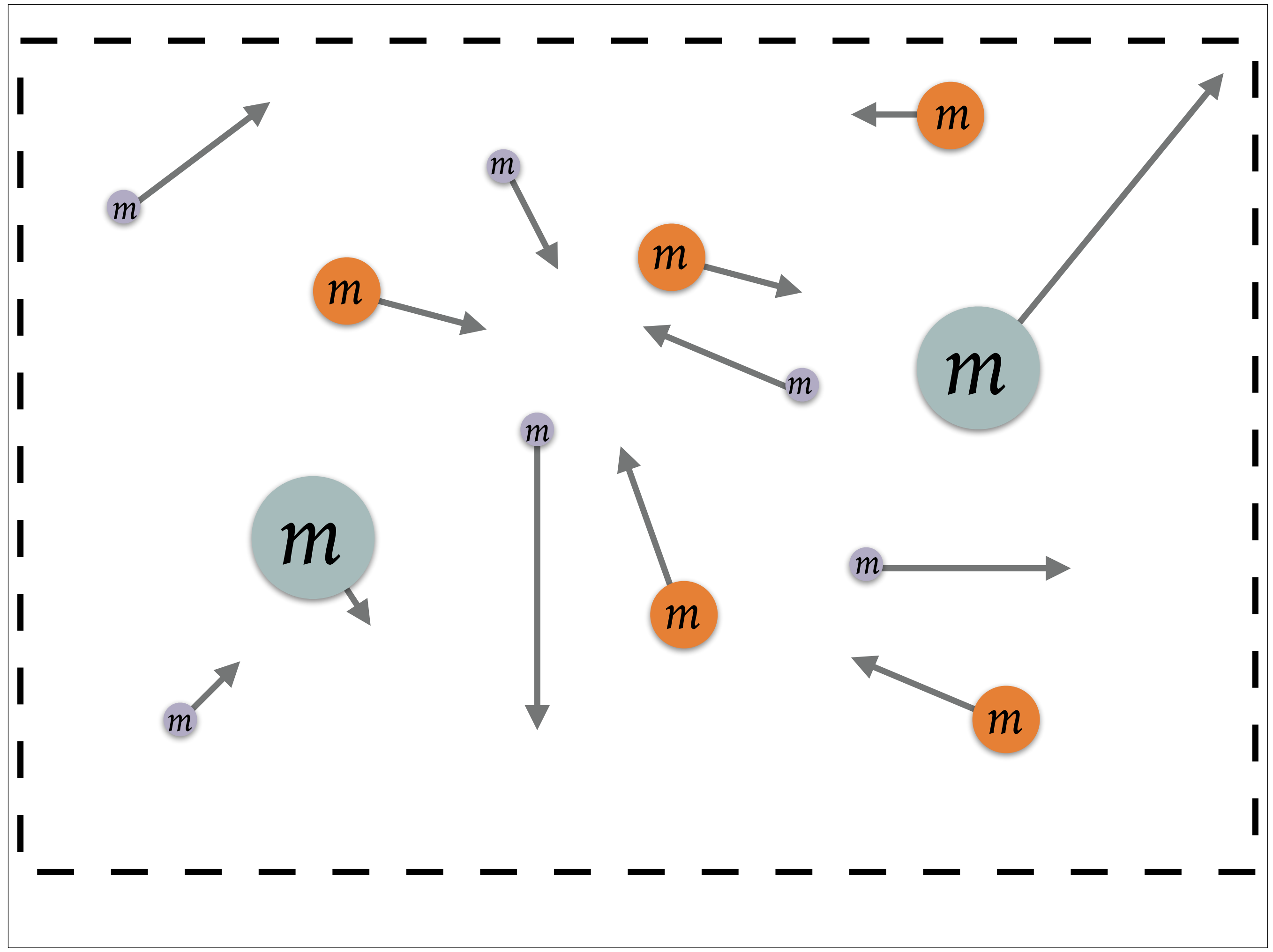
MOMENTUM

The quantity of motion

- Demo collisions with different masses

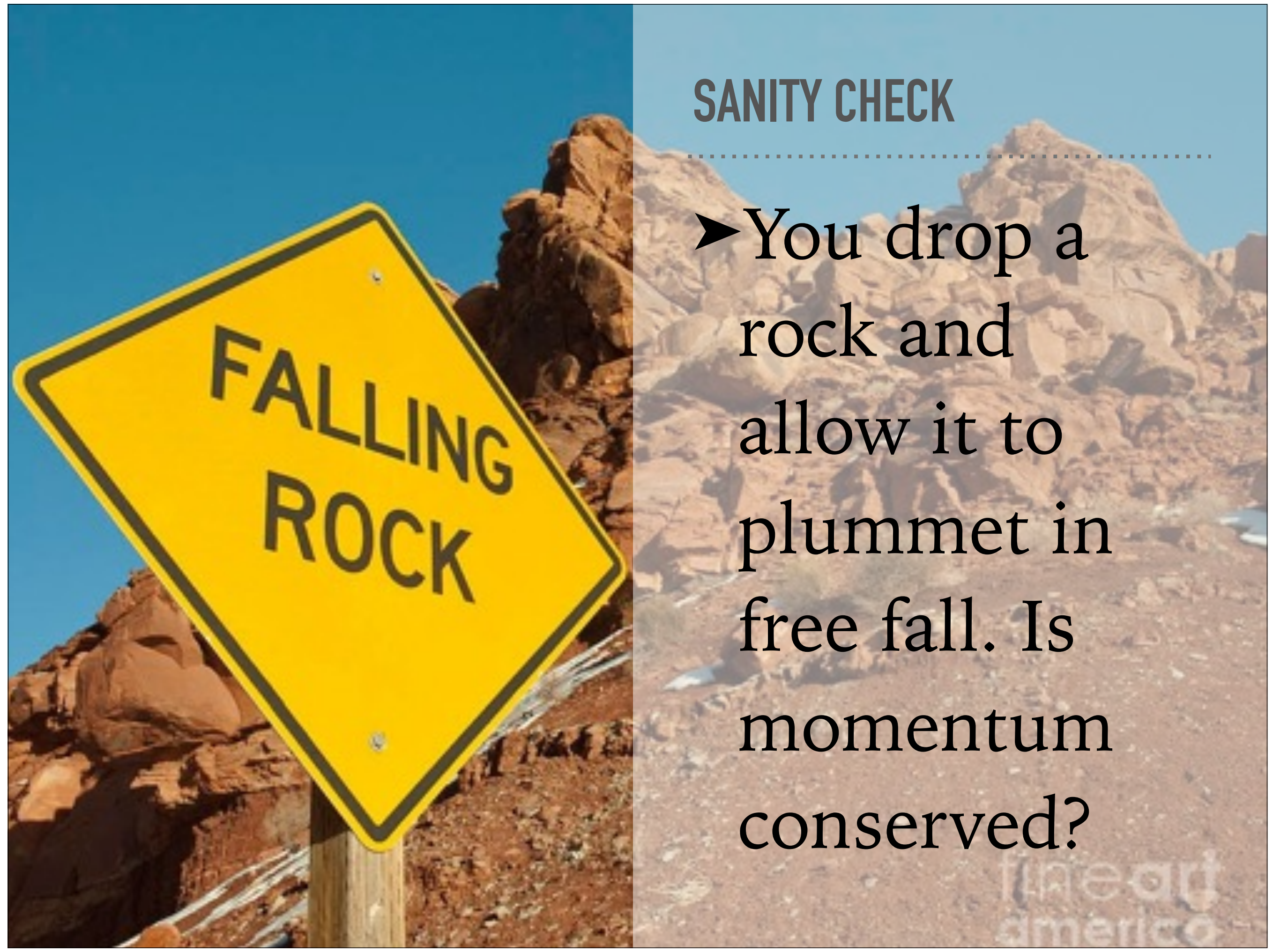
$$\mathbf{p} = m\mathbf{v}$$

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



- Individual momenta might change, but as long as nothing leaves and nothing new enters, the total momentum will remain the same

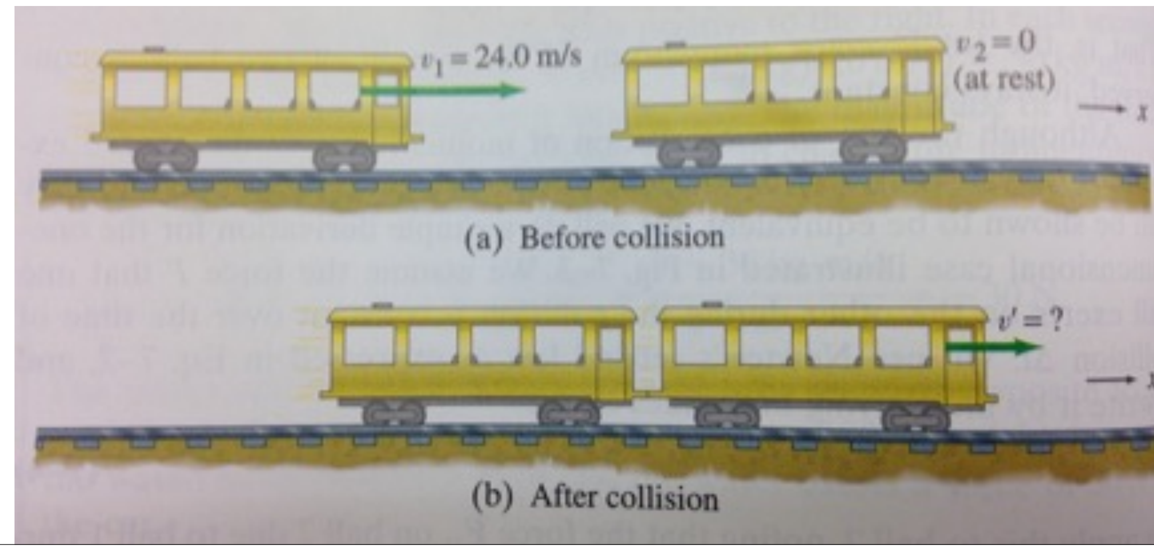
> The total momentum of an isolated system remains constant
>
> *The Law of Conservation of Momentum*



➤ It is if you include the Earth

PRACTICE VII: TRAIN COLLISION

- 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?

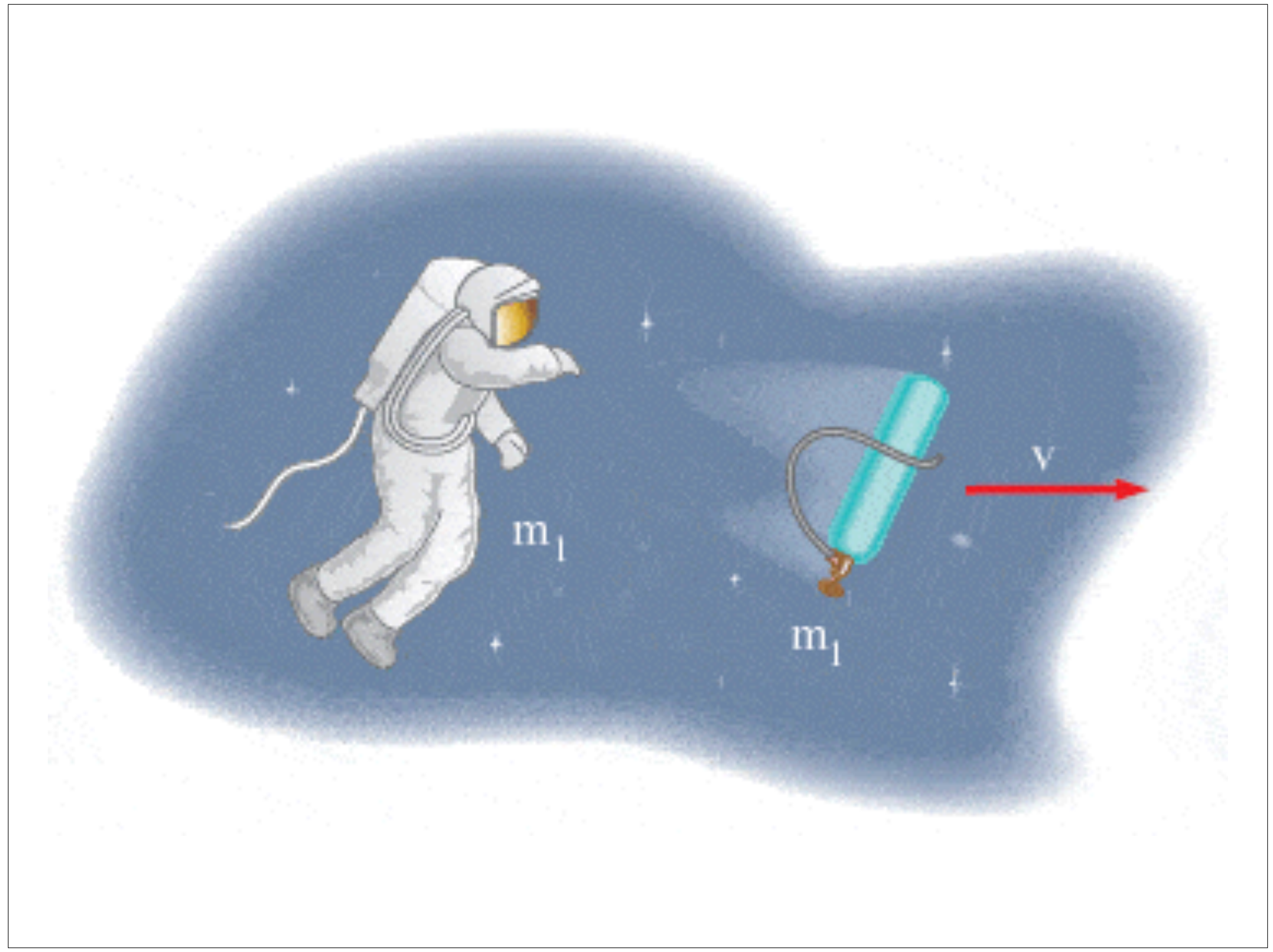


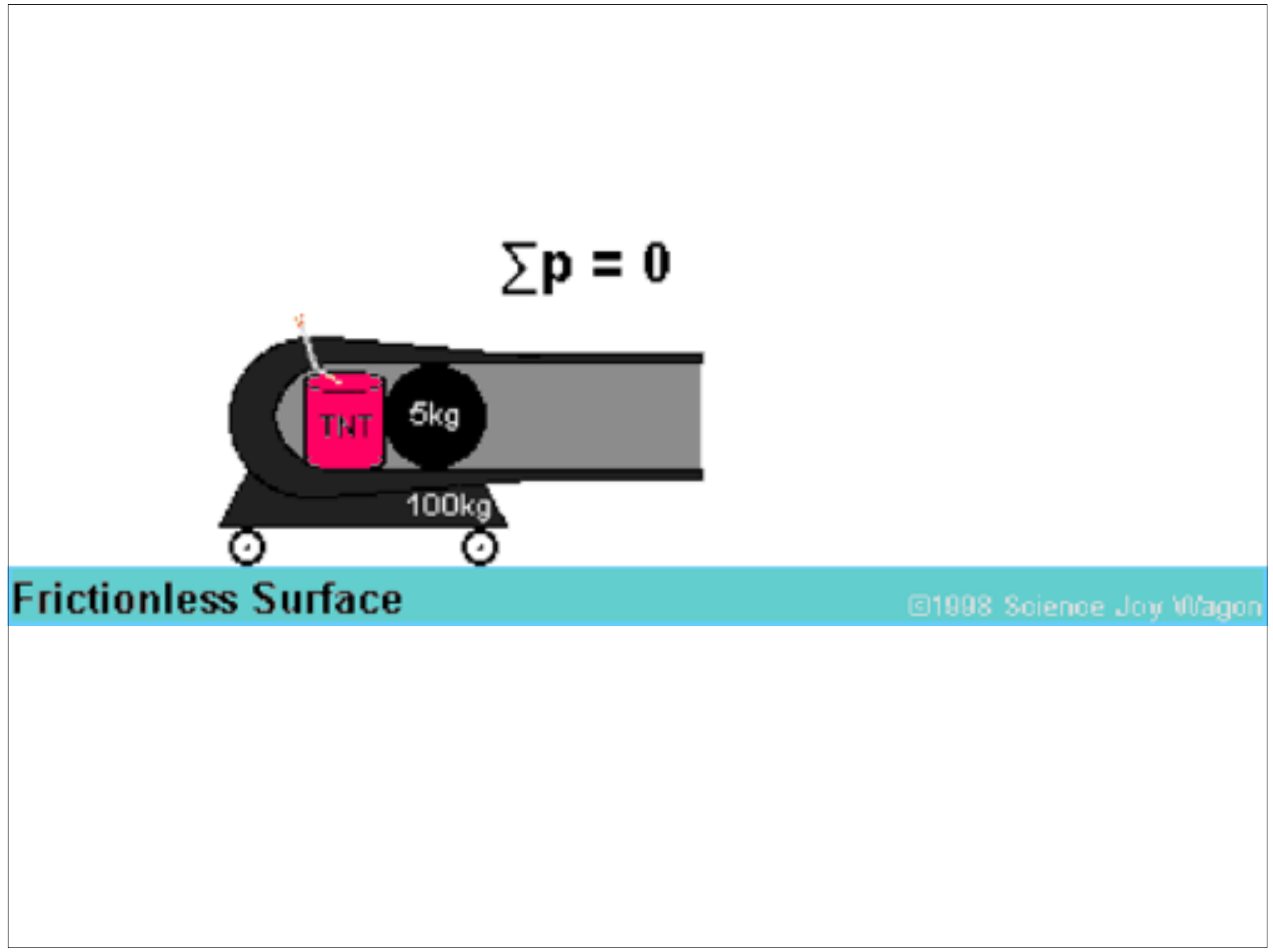
(a) Before collision

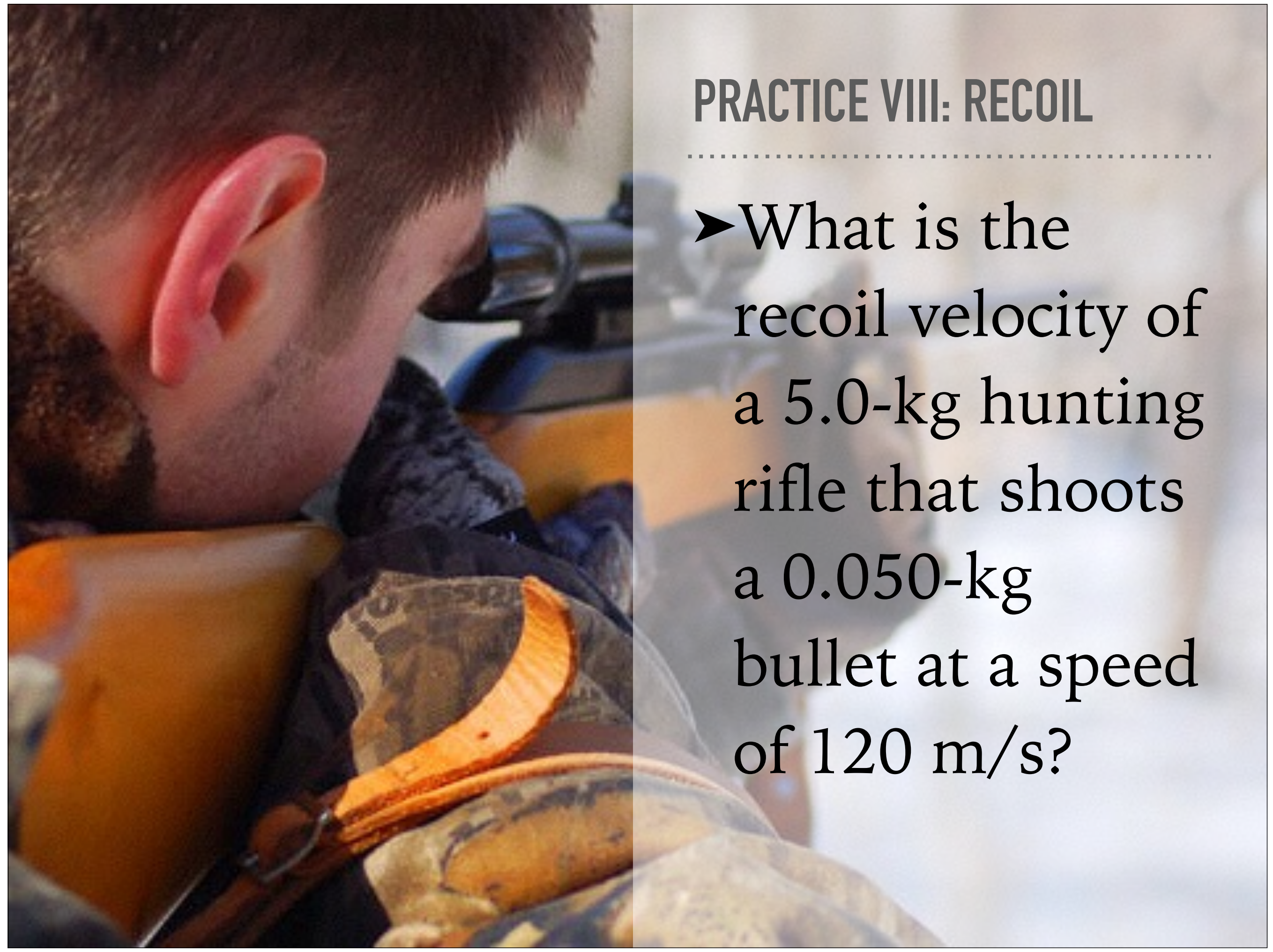
(b) After collision

- Answer: $v_f = 12$ m/s

- upward momentum of rocket = downward momentum of exhaust


m1
m1
v


∑p = 0
TNT
5kg
100kg
Frictionless Surface
©1998 Science Joy Wagon



- Answer: v_R' = -1.2 m/s

The Second Law of Motion

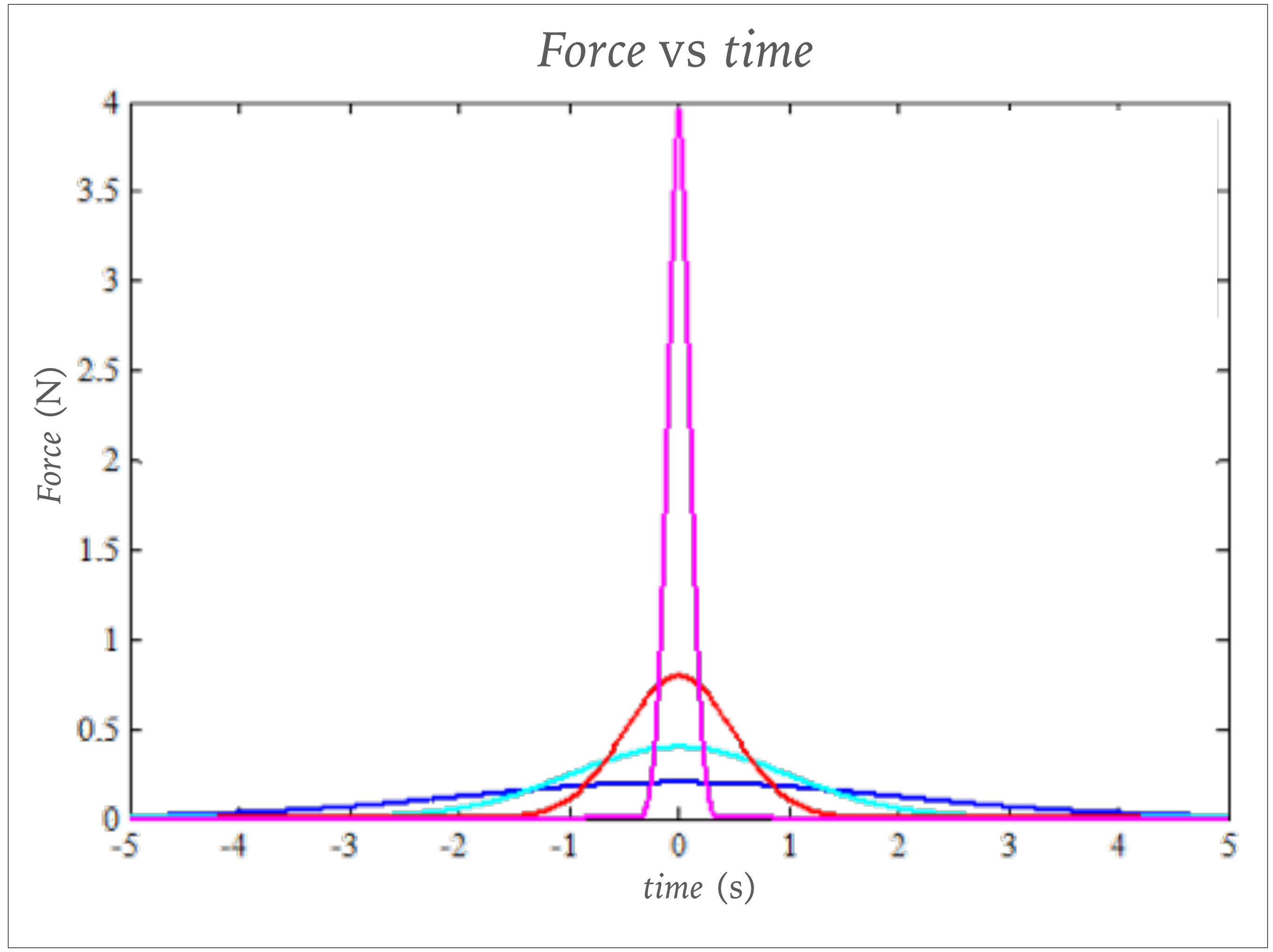
$$\mathbf{F}_{\mathrm{net}} = \frac{d\mathbf{p}}{dt}$$

*the **net force** = rate at which **momentum** changes with **time***

Impulse

$$\Delta p = \int F_{net}\, dt$$

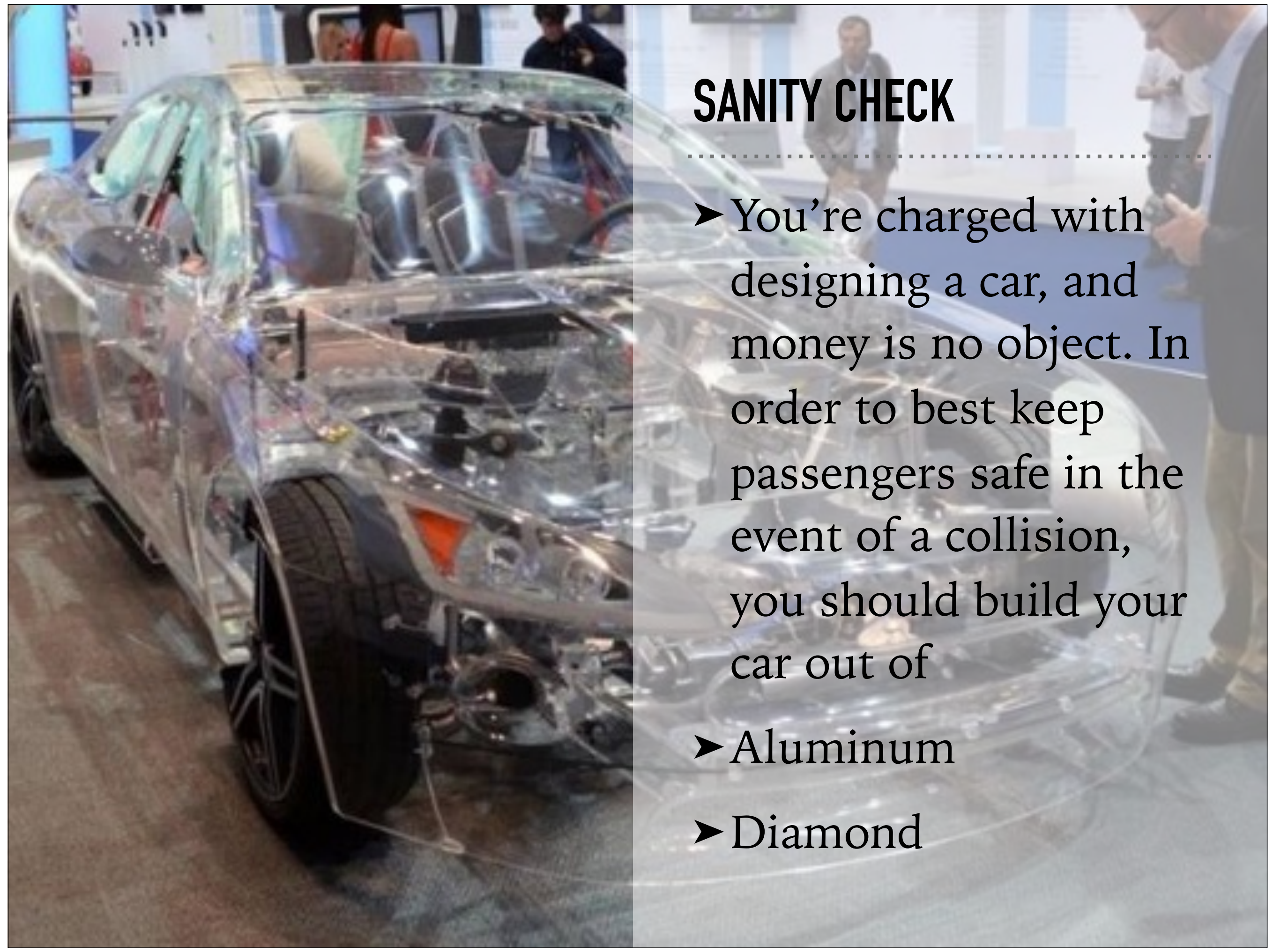
*change in **momentum** = the **net force** integrated over **time***



- In all cases, the impulse is the same

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?



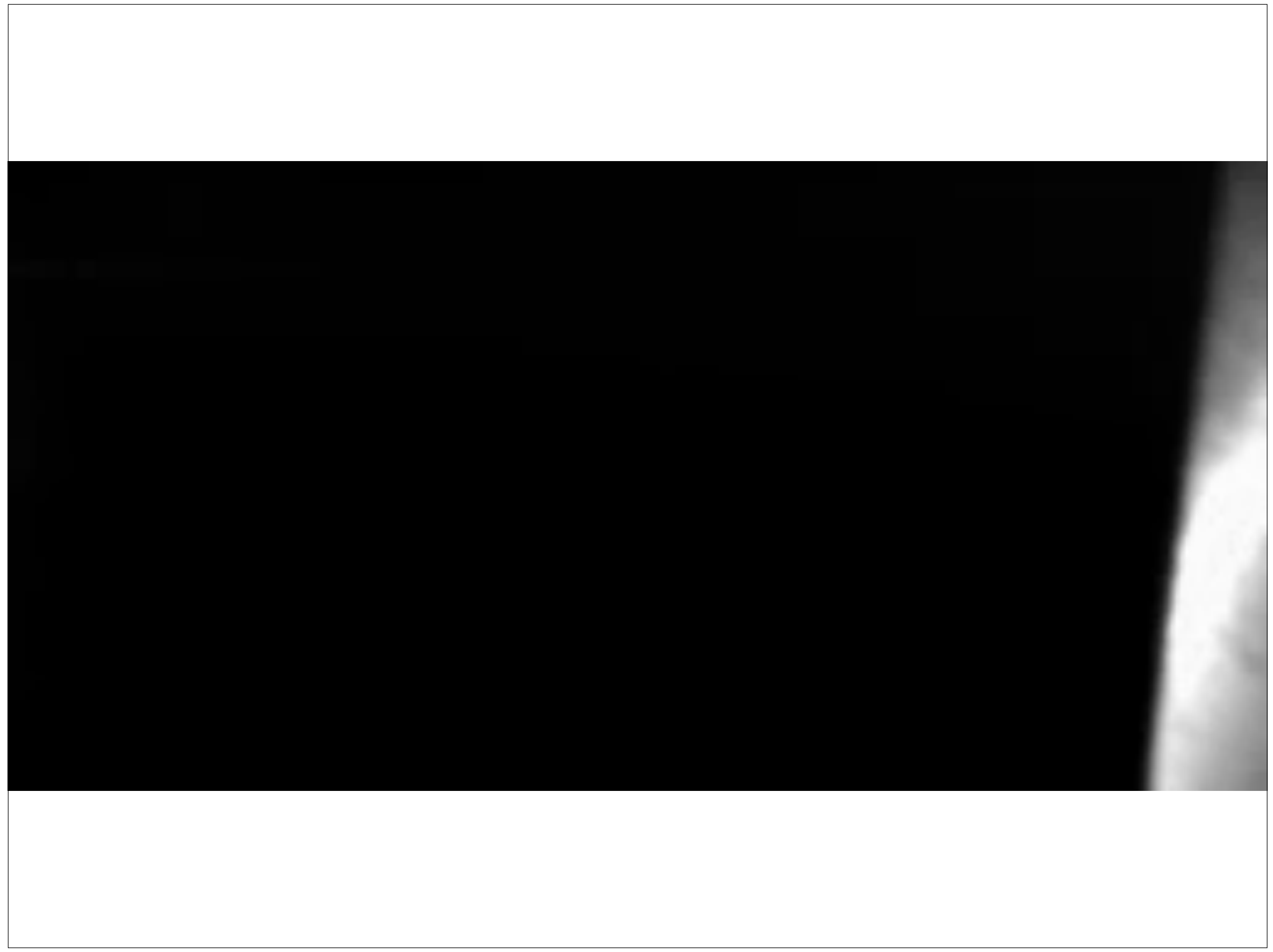
SANITY CHECK

- 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

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
- https://www.youtube.com/watch?v=00I2uXDxbaE

- Karate chop deformation
- https://www.youtube.com/watch?v=otHZwjElXwQ

PRACTICE IX: HOCKEY SHOT

- How hard would a puck have to be shot to be able to knock the goalie himself backward into the net?
- What would you need to know in order to answer this question?

- m_{puck} = 165 g, $F_{fr} \approx 800$ N (from $m_{goalie} \sim 100$ kg, $\mu_s \sim .80$), t ~ 0.5 s
- $F_{fr}\,\Delta t = \Delta p = m_{puck}\Delta v \rightarrow v \approx 2400$ m/s ≈ mach 7

PRACTICE X: MACHINE-GUN JETPACK

- Is it possible to build a jetpack using downward-firing machine guns?
- What would you need to know in order to answer this question?

- The amount of thrust created by a rocket (or firing machine gun) depends on (1) how much mass it's throwing out behind it, and (2) how fast it's throwing it

PRACTICE X: MACHINE-GUN JETPACK

- If an AK-47 fires ten 8-gram bullets per second at 715 m/s, what is the force of thrust is generates?

- Answer: F_{thrust} = 60 N
- A fully loaded AK-47 weighs about 47 N, so it could take off, but it doesn't have enough spare thrust to lift anything heavier than a squirrel

PRACTICE X: MACHINE-GUN JETPACK

- If an AK-47 produces about 60 N of thrust and each gun weighs 47 N, how many would you need to lift a 70 kg person?

- Answer: at least 70
- One major problem with this jetpack (one of many) is that an AK-47 magazine only hold 30 rounds
- At 10 rounds per second, this would provide a measly three seconds of acceleration
- We can improve this with a larger magazine, but only up to a point. Why? (more ammo = more weight)

COLLISIONS

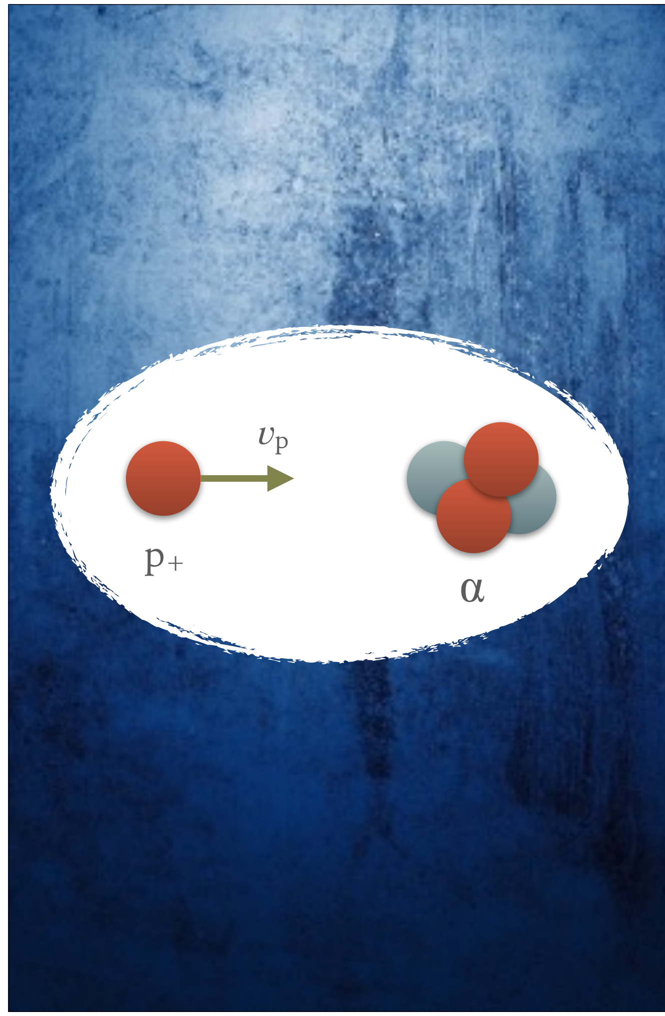
- *Elastic Collision* — a collision during which no deformation takes place (or at least very little)
- *Inelastic Collision* — a collision during which deformation takes place
- *Perfectly Inelastic Collision* — a collision where the objects stick together after colliding

- Explosions are basically perfectly inelastic collisions run in reverse

PRACTICE XI: BILLIARDS

- A billiard ball of mass m moving with speed v collides head-on with a second ball of equal mass at rest. What are the speeds of the two balls after the collision, assuming it is elastic?

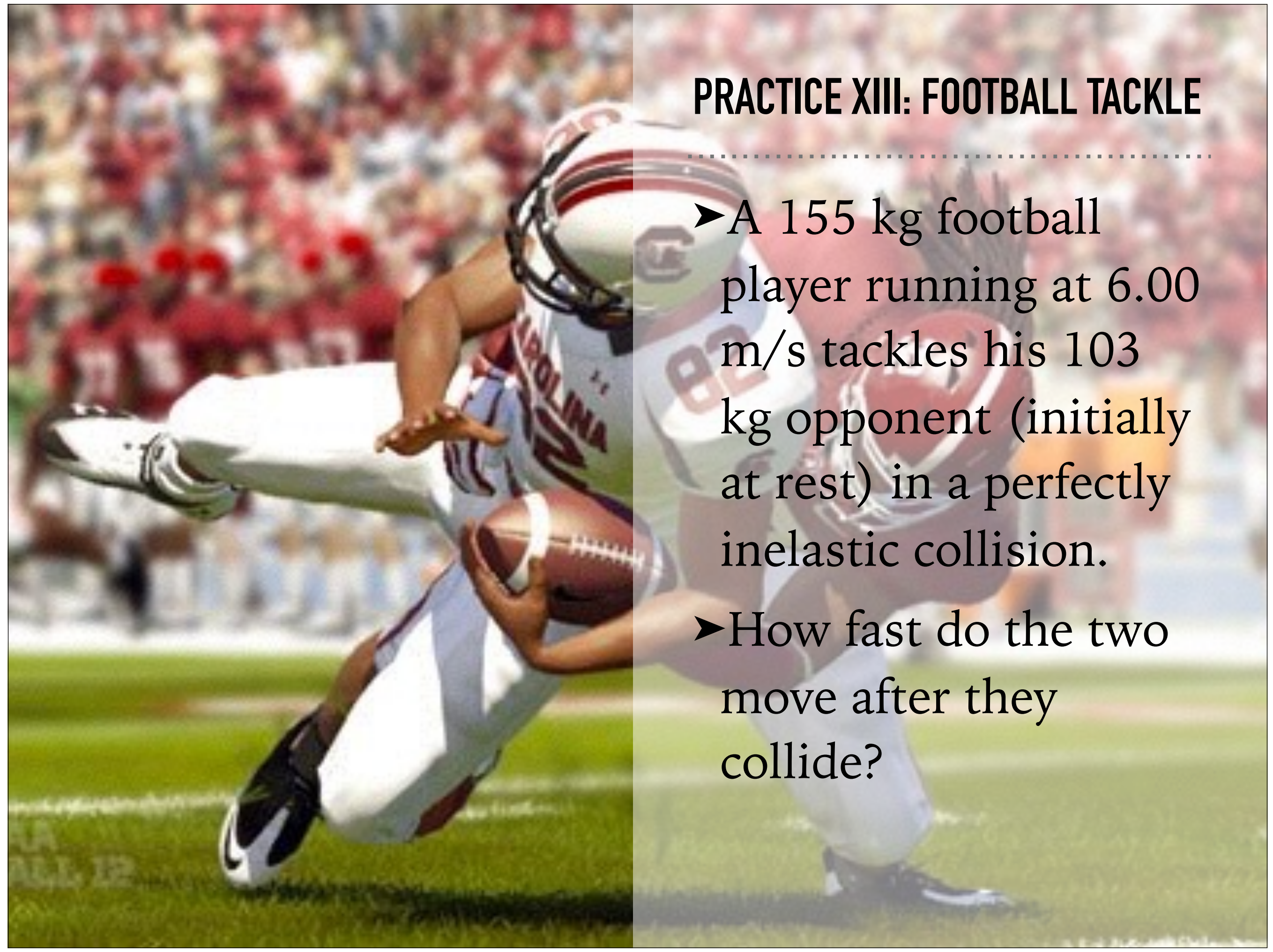
- Answer: $v_1' = 0$, $v_2' = v$



PRACTICE XII: PARTICLE COLLISIONS

- A proton of mass $m_p = 1.67 \times 10^{-27}$ 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; $m_\alpha = 6.64 \times 10^{-27}$ 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: $v_\alpha' \approx 2 \times 10$ m/s



- Answer: $v_f \approx 4$ m/s

PRACTICE XIV: ELASTIC VS. INELASTIC

- Two spheres, both with mass *m* and speed *v*, collide head-on. Calculate the velocities after the collision assuming the collision is (a) perfectly elastic and (b) perfectly inelastic.

Answers:
(a) $v_1' = -v$, $v_2' = +v$
(b) $v' = 0$