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# The Physics of Sports: a Textbook (with answers)

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# Physics of Sports-a Textbook

(with answers)

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Note from D. Heskett:

This book is intended to accompany a one-semester general education college science course, largely conceptual with some simple quantitative and semi-quantitative content. No previous physics background is necessary. Some math is needed - simple algebra and arithmetic. Questions and exercises are embedded throughout the text. I have also included homework questions and exercises for each chapter, most with answers (in one version). The book may also be appropriate for a high school physics course?

The book is constructed around various sports images and videos; with most of the videos from some Dvd's or from YouTube clips. I have put this together over a few years time, so it is entirely possible that some of the links I have referenced have changed since then or are no longer valid. In addition, some of the world records I discuss may have been broken!

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# CHAPTER 1: Motion in One Dimension


Track star Usain Bolt of Jamaica

http://www.telegraph.co.uk/sport/othersports/olympics/2570015/Usain-Bolt-smashes-world-100-metres-record-at-Beijing-Olympics.html


VIDEO 1.1: 100 meter men's finals at the 2008 Olympic games

https://digitalcommons.uri.edu/physicsofsports/1/

## 1.1: Distance and Speed

In physics we want to be able to describe motion in a precise and useful manner. (The study of motion is referred to as "kinematics".) In our everyday world we talk about "how far" and "how fast". What do those mean exactly and how do we express them in the language of physics? Click the link above and watch VIDEO 1.1.

### DISTANCE

You just watched a video of Usain Bolt setting a world record in the 100 meter sprint at the 2008 Olympic games in Beijing. (Since then he has broken his own world record.) The answer to "How *far* did Usain Bolt run?" is pretty obvious - 100 meters. In physics we don't use the term "far" but instead talk about **distance**, a term we also use in our everyday world. In this case the distance of his race was (also) 100 meters. (A related term **displacement** is also used - more on that later.)

### Unit Conversion #1

In physics the standard system of units is the "SI" system. The basic unit of length is the meter, the basic unit of time is the second, and other units we will get to later as needed. These units are sometimes used in our everyday world (e.g. the 100 meter dash) but we want to be able to relate physics units to our everyday units as well.

Let's start with length. A meter stick is slightly longer than a yard stick, so a meter is slightly more than 3 feet. In particular, 1 meter = 3.28 feet.

QUIZ 1.1

Usain Bolt's 100 meter sprint corresponds to a distance slightly more than which of the following?

( x ) 100 yards
( ) 150 yards
( ) 200 yards
( ) 300 yards
( ) 400 yards

Usain Bolt's record run covered a distance of slightly more than 300 feet or 100 yards (the length of a football field). The exact conversion goes as follows:

$$(100 \text{ meters}) \times (3.28 \ \frac{\text{feet}}{\text{meter}}) = 328 \text{ feet.}$$

QUIZ 1.2

Convert a length of 200 meters to feet.

( ) 164 feet
( ) 328 feet
( x ) 656 feet
( ) 984 feet

## SPEED

The next issue worth discussing concerning Usain Boldt's run is the question of "how fast?" Obviously, it was not the length of the run that was noteworthy (most of us could run 328 feet given enough time), but the (short) time it took him to complete it.

How much time did it take for Usain Bolt to run 100 meters?

Select the video again and watch Bolt and the clock to find the time it took him to run 100 meters in world record time:

QUIZ 1.3

time = __________ seconds

Answer: ~10 seconds (actually 9.69 seconds)

Now we can answer the question of "how fast" Usain Bolt ran. We take the distance and divide this by the time to get the **speed** (again pretty much the same as we use in our everyday world). We'll use the official time of 9.69 seconds. (Was this close to your answer?)

$$\text{speed} = \frac{\text{distance}}{\text{time}} \qquad \text{Equation 1.1}$$

For Bolt's 100 meter race,

$$\text{speed} = \frac{100\,\text{meters}}{9.69\,\text{seconds}} = 10.3\ \text{meters per second or } 10.3\ \text{m/s}$$

Note that the SI unit of speed is the meter per second which is abbreviated m/s.

## Unit Conversion #2

How "fast" is a speed of 10.3 meters per second anyway? The speed unit we are most familiar with in our everyday world is miles per hour (mph). To appreciate Bolt's speed let's convert his speed in meters per second to miles per hour. We need to know the conversion between meters and miles and between seconds and hours.

1 hour = 3600 seconds

1 mile = 1609 meters

Putting this together:

$$1\text{ mph} = \frac{1609\text{ meters}}{3600\text{ seconds}} = 0.447\text{ m/s}$$

or

$$1\text{ m/s} = \frac{1}{0.447} = 2.24\text{ mph}$$

Now we are ready to convert Bolt's speed to miles per hour:

$$10.3\text{ m/s} = (10.3\text{ m/s})(\frac{2.24\text{ mph}}{\text{m/s}}) = 23.1\text{ mph}$$

That's fast!

(That's close to the speed limit for a car driving through a small town, usually ~25 mph.)

## QUIZ 1.4

At the same Olympics in 2008, Usain Bolt also set a new world record in the 200 meter dash (a record he also later broke in 2009). How do you think his speed in the 200 meter dash compared to the 100 meter record we already discussed?

( ) Probably about the same speed.
( ) Greater speed for the 200 meter race since the distance was longer.
( ) Lower speed for the 200 meter race since the distance was longer.

QUIZ 1.5

Calculate the speed for the 200 meter race. Bolt's official time was 19.30 seconds.

speed = ___________ meters per second

(Answer: 10.4 meters per second)

Bolt's speed was slightly *greater* for the longer distance. Some people (me included) would have guessed that his speed would decrease running the longer distance. Not the case though the speeds were very close.

- Can you think of an explanation for the (slightly) greater speed for the longer race?
- Do you think this trend of a faster 200 meter race vs. 100 meter race for runners who do both events is "normal" or not? You could research other race results and find out.

Now, let's look at some speeds in other sports and compare them to Bolt's records. How do you think his speed will stand up compared with other sports?

First, Michael Phelps set a world record in the 100 meter butterfly swimming event at the 2009 World Championships in Rome.

QUIZ 1.6

How do you think the time of Phelps' 100 meter world record compares to the time of Boldt's 100 meter world record?

( ) Probably about the same time
( x ) Greater time for Phelps' race
( ) Greater time for Boldt's race


VIDEO 1.2: 100 meter butterfly final at the World Championships in Rome, 2009

https://digitalcommons.uri.edu/physicsofsports/2/

QUIZ 1.7

Click the link for VIDEO 1.2 and watch the swimmer (Phelps) and the clock to find the time it took Michael Phelps to set this world record:

a. time = ___________ seconds

(Answer: 49.82 seconds)

Now calculate the speed using the official time of 49.82 seconds.

b. speed = ___________ meters per second

(Answer: 2.0 meters per second)

Compared to Bolt's run, Phelp's world record swim took considerably more time to complete (is that what you guessed?) so his speed was less. Why is that?

Another example: here's a video from baseball. Ichiro Suzuki from the Seattle Mariners steals second base.

VIDEO 1.3: Ichiro Suzuki steals 2nd base in June, 2008
(Seattle Mariners vs. New York Yankees)

https://digitalcommons.uri.edu/physicsofsports/3/

QUIZ 1.8

Click the link for VIDEO 1.3 and watch the runner and use a clock or stopwatch to estimate the time it took Suzuki to steal second base:

a. time = ___________ seconds

(Answer: 3 seconds)

I got a time of ~3 seconds. How about you? Now calculate the speed using the time of 3 seconds and a distance between the bases of 90 feet = 27.4 meters

b. speed = ___________ meters per second

(Answer: 9.1 meters per second)

(Actually a more accurate distance for this base stealing calculation would be 85 feet = 25.9 meters. Why is this a better distance choice?)

In the table below I have collected a variety of top speeds from different sporting events.

| Sport | Athlete | Distance | Time | Avg. Speed (m/s) | Avg. Speed (mph) |
|---|---|---|---|---|---|
| | | | | | |
| Running | U. Bolt | 100 m | 9.69 s | 10.3 m/s | 23.1 mph |
| Swimming | M. Phelps | 100 m butterfly | 49.82 s | 2.0 m/s | 8.96 mph |
| Baseball:Base Stealing | I. Suzuki | 27.4 m | 3 s | 8.7 m/s | 19.5 |
| Football:Running for a Pass | J. Rice | 27.4 m | 4 s | 6.9 m/s | 15.5 |
| Biking-200 m time trials | C. Hoy of Great Britain won Gold at the 2008 Olympics | 200 m | 10.216 s | 19.6 m/s | 43.9 |
| Skiing-Women's Giant Slalom | Viktoria Rebensburg of Germany wins Gold at the 2010 Winter Olympics | 1602 m | 147.11 s | 10.9 m/s | 24.4 |
| Wheelchair race | Lucas Prado from Brazil won Gold at the 2008 Paralympic Games | 100 m | 11.03 s | 9.1 m/s | 20.4 |
| Pole vault approach | Steve Hooker from Australia won gold at the 2008 Summer Olympics | $\geq$ 40 m | 5 s | $\geq$8 m/s | 17.9 |
| 4 man bobsled | U.S. team-Gold in 2010 Olympics | 1450 m | 214.46 s | 6.8 m/s | 15.2 |
| Speed Skating (short track) | Apolo Ohno won Gold at the 2006 | 500 m | 41.935 s | 11.9 m/s | 26.7 |

| | | | | | |
|---|---|---|---|---|---|
| | Winter Olympics | | | | |

Table 1.1
Athlete Speeds in Sports

For the table above, I did some estimates of distances from some of the videos and converted units where necessary.

From the table, we can see a wide variation in speeds in various sports - no surprise since we are comparing quite different activities.

QUIZ 1.9

In the table above, there were only two sports with speeds significantly greater than the speed of Usain Bolt in the 100 meter dash (the giant slalom result was pretty close to Bolt's speed). Which are they?

______________

______________

(Answers: biking
speed skating)

## PROJECTILES

In many sports, it's not the speed of the athlete that matters; the speeds of projectiles (various balls, the discus, the javelin, hockey puck, etc.) are often important. Let's consider a variety of projectile speeds.

### QUIZ 1.10

Rank how you think the top speeds of the projectiles listed below compare:

A Speed of a fastball in baseball
B Bowling ball just after release
C Slap shot in hockey
D Tennis serve
E Soccer kick

Now we'll collect these and a few other results together below:

Table 1.2
Projectile Speeds in Sports

| Sport | Projectile | Situation | Speed (m/s) | Speed (mph) |
|---|---|---|---|---|
| | | | | |
| Tennis(1) | tennis ball | serve (in 1931) | 73 m/s | 163 mph |
| Baseball | baseball | fastball leaving pitcher's hand | 45 m/s | 100 mph |
| Baseball | baseball | baseball leaving bat for a home run ball | 49 m/s | 110 mph |
| Soccer | soccer ball | penalty kick | 36 m/s | 80 mph |
| Shut put | shot | just after launch | 14 m/s | 31 mph |
| Hockey | puck | slap shot | 54 m/s | 120 mph |
| Cricket | cricket ball | bowling | 90 m/s | 201 mph |
| Jai-alai | pelota | "throw" (in 1979) | 84 m/s | 188 mph |
| Badminton | shuttlecock | smash | 92 m/s | 206 mph |
| Hurling | sliotar | strike | 45 m/s | 100 mph |
| Football (2) | football | long pass | 33.5 m/s | 75 mph |
| Bowling | bowling ball | fastest recorded | | 35 mph |

**http://hypertextbook.com/facts/2001/TinaCheung.shtml**

(1) Bill Tilden in 1931
(2) Brett Favre

Any surprises? (What's hurling? What's a sliotar? - Look it up.)

Did you get the ranking correct?

D > C > A > E > B

I would not have guessed that projectiles in lesser-known sports (lesser-known in the U.S. anyway) would have speeds measured in the 200 mph range. Also I would never have guessed that a tennis ball had been hit at 163 mph and that it occurred in 1931, not in more modern times (at least according to my research).

Let's take a brief look at the sport of jai-alai, called by some "the world's fastest ball game." Click on the link for VIDEO 1.4 and watch a clip from a jai-alai match.

VIDEO 1.4: Jai-alai in action.

https://digitalcommons.uri.edu/physicsofsports/4/

I don't know if the "pelota" reached 188 mph in this video, but it certainly was traveling very fast!

# 1.2:  Speed and Velocity

## SPEED VS. VELOCITY

In our everyday world, we use the terms "speed" and "velocity" interchangeably. In physics, these terms are very specific (as are most things in physics!) and refer to different things.  (Average) speed (distance divided by time) we've already discussed and illustrated. **Velocity**, simply put, means "speed" plus "direction". In physics, something that has a value (called a "magnitude") and a direction is called a "vector". Velocity is one of many vectors used in physics. Displacement (change in position) mentioned earlier is also a vector. More on vectors later.

Because of the directional property of velocity, the velocity of a person, ball, bicycle, car, etc. can change even if the speed does not change. Let's examine a few situations:

Click on the link for VIDEO 1.5 and watch a short segment of a 10,000 meter race (a "10K" race since 10,000 meters = 10 kilometers) from the 2008 Summer Olympics. To run 10,000 meters, the runners must circle the track 25 times. (The winning time by Kenenisa Bekele was just over 27 minutes.) In the middle of the race, it's a good assumption that the speed is close to being constant. What about the velocity?


VIDEO 1.5:  Segment of the 10,000 meter race from the 2008 Olympics.

https://digitalcommons.uri.edu/physicsofsports/5/

QUIZ 1.11

What can we say about the velocity during a 10 K race? (Let's consider the runners while they cover one full lap in the middle of the race and let's assume their speed was constant throughout.)

( ) The speed was constant so the velocity was also constant.
( x ) Since the runners changed direction as the they circled the track, their velocity changed during the race.
( ) Not enough information is given to determine if the velocity changed or not.

The direction changed so the velocity changed. Did you get that?

Here's another sport, curling, which became quite popular during the 2010 Winter Olympics.

Click the link for VIDEO 1.6 and watch a segment of a curling competition from the 2010 Winter Olympics.

VIDEO 1.6: Curling competition from the 2010 Winter Olympics.

https://digitalcommons.uri.edu/physicsofsports/6/

QUIZ 1.12

What can you say about the speed and velocity during the video of curling you just watched?

( ) The speed was constant but the velocity changed.
( ) The velocity was constant but the speed changed.
( ) Both speed and velocity were constant.
( x ) Both speed and velocity changed.

If there was any change in the direction of the "stone" in this curling event it was not obvious. However, the speed obviously changed since the stone eventually slowed to a stop (or at least almost to a stop before the stone was removed from play). Since speed changed, velocity changed as well. (In some curling "ends" the direction of the stone will also change due partly to the (intentional) action of the "sweepers".)

There are not many sports in which the direction and/or speed of the principle object does not change, so generally the velocity of a sports object (and of most objects in the real world) will not be constant. Can you think of any sports examples in which the speed of a primary object is constant and/or in which the direction does not change?

## AVERAGE VS. INSTANTANEOUS SPEED

In the previous section we watched a video of curling in which the speed of the stone clearly changed as it slowed down to zero. For a middle segment of the 10K race, we assumed the speed was constant though the direction changed. But obviously even if the speed was constant during this segment (a good but probably not completely accurate assumption) the speed was certainly <u>not</u> constant during the entire race. Why not?

QUIZ 1.13

Why can we be sure the speed <u>during</u> the 10K race was not constant throughout? Give the <u>best</u> answer.

( ) The racers may get tired and slow down at the end of the race.
( ) The racers slow down after they cross the finish line.
( ) The racers may increase their speed at the end of the race to get across the finish line.

( x )  The racers all started the race from a standstill so the speed of each racer must have increased at the beginning of the race.

The speeds of the runners (or cyclists or swimmers, ...) in any race may change frequently or may not, but it is certain that the speed right at the start of almost any race is zero and the speed increases from there. So when we discussed and calculated the "speeds" of runners, swimmers, bikers, skiers, etc. previously, we were really considering the average speeds of the athletes. The speed at any particular moment in time is referred to in physics as the "instantaneous speed."

It is difficult to determine an instantaneous speed just by watching a video, but we can examine average speeds at different times during a race and see what we can learn from that. Let's return to the video of Bolts's world record 100 meter dash. Let's examine the start and end of this race more carefully and find the average speeds at the beginning and end of the race. What do you think we will find?

QUIZ 1.14

What do you predict about the average speeds at the beginning and end of the Bolt's 100 meter dash?

( )  The average speed will be greater at the beginning of the race.
( x )  The average speed will be greater at the end of the race.
( )  The average speed will be the same at the beginning and end of the race.

Let's find out. Select the video again (VIDEO 1.1) and watch the runner and the clock and find the times that Bolt ran at the beginning and end of his race. Specifically when Bolt crosses the yellow line near the beginning of the race he has covered a distance of ~12 meters. Near the end of the race he crosses a blue line which is ~9 meters from the finish line. Do the best you can!

QUIZ 1.15

a. time to yellow line ___________ seconds

b. time from blue line to finish line ___________ seconds

My anaysis yielded the following results:

a. time to yellow line: 1.6 seconds

b. time from blue line to finish line: 1.0 second

(How do your times compare to mine?)

QUIZ 1.16

Now use my results to find the average speeds:

a. average speed for 1st 12 meters = ___________ meters per second

b. average speed for last 9 meters = ___________ meters per second

(Answers: a. 7.5 meters per second
b. 9.0 meters per second)

As I expected (how about you?), because Bolt started from rest, the average speed for the first segment is less than Bolt's average speed for the last segment of the race. If we were able to keep shrinking the time interval to shorter and shorter times, we would approach the "instantaneous speed" at a given position/time in the race. This is hard to do by just watching a video but can be done with the help of a computer as we will see in the next section. (We can also find instantaneous speeds in some cases by the use of calculus - but not in this book!)

# 1.3: Velocity and Acceleration

## GRAPHICAL ANALYSIS

Now we want to take a different kind of look/analysis of one-dimensional motion. In physics, we do a lot of graphing or plotting of various quantities to obtain a variety of useful information. Here we want to prepare a plot of the distance that an athlete ran as a function of time. This could be done, as alluded to in the previous section, by recording the distances he/she covered over very small time intervals. Much easier and more accurate is to use a computer to help us plot and analyze this information.

QUIZ 1.17

What we will do now is what we call "digitizing" a video. If you were doing the analysis yourself, you would run the video, advancing frame by frame and stop at every frame (or set of fames). At each pause, you would place your cursor on the middle of the runner's waist as well as you can and click once. A dot should appear. Then advance to the next frame. Usain Bolt wasn't available for this analysis so a local yoga instructor and all-around superb athlete volunteered to substitute! (Click on the link below and watch VIDEO 1.7.) (You could also take a shot at a similar analysis of Bolt's race in VIDEO 1.1. But there are challenges! What are they?)


VIDEO 1.7: Track sprint

https://digitalcommons.uri.edu/physicsofsports/7/

My analysis of this sprint is presented below. First a plot of position vs. time.

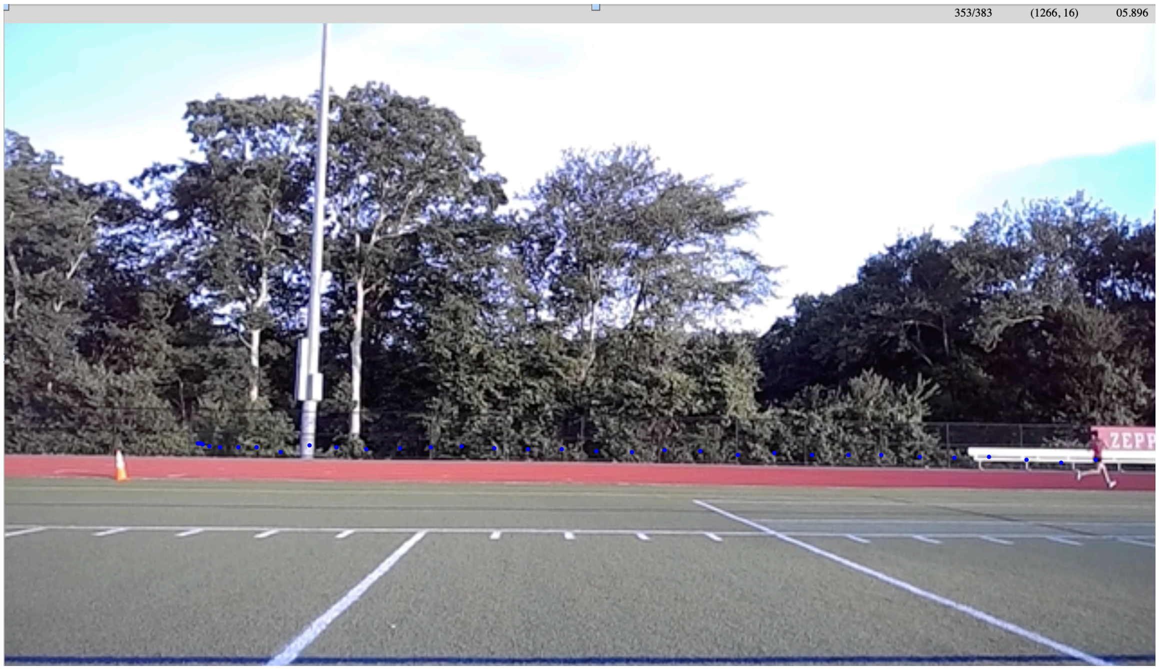



FIGURE 1.2: Digitization of VIDEO 1.7 (I used every 10th frame to generate this plot)

From the spacing of the points in the plot of position of the runner vs. time (the blue dots-this may be easier to see in Figure 1.3 below), we note that the distance covered in each time interval increases as the time increases. This makes sense as the runner started the race at a stop, then as the race progresses her speed (and velocity) increased so the distance covered in each second increased as well.

Now we will let the computer turn this plot into velocity vs. time:

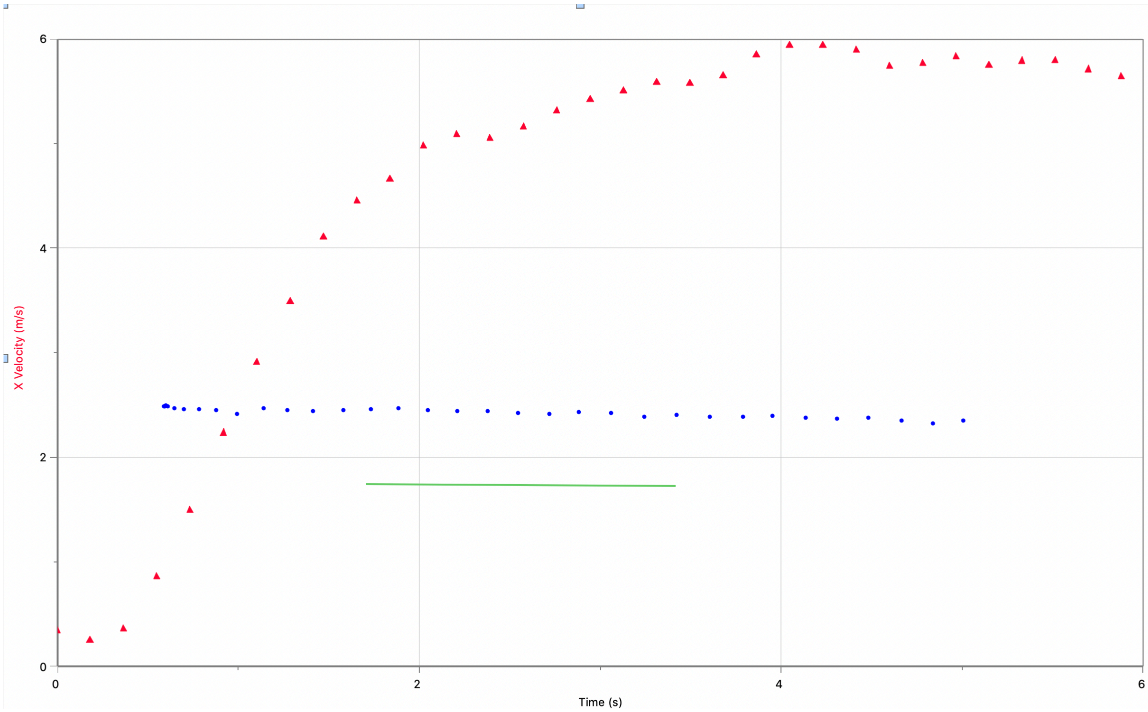



FIGURE 1.3: Plot of Velocity vs. Time taken from the digitization of VIDEO 1.7.

The computer has now calculated and plotted the <u>instantaneous</u> velocity (speed) as a function of time. As we expected, the speed increases as the race proceeds. The increase in speed is more or less linear for the early and later portions of the run. However, the slopes are clearly different, greater for the first ~2 seconds.

To generate this plot of velocity vs. time, the computer took the slope of the distance vs. time curve at every point. Since speed is distance divided by time, <u>the slope</u> (or "rise over the run") <u>of a distance vs. time plot gives the speed</u> (technically the velocity since the slope could be negative).

## ACCELERATION

When the velocity of an object changes, in physics we say that the object experiences **acceleration** which is a change in velocity vs. time, pretty similar in some cases as we would use the term in the everyday world. In the previous plot of velocity vs. time, we say that the runner accelerated because her speed changed. But this is not the only way that acceleration can occur. Let's consider some other examples:

QUIZ 1.18

In which race is the runner accelerating (choose all that apply)? Remember that acceleration involves a change in vleocity.

( x ) During a 50 meter dash the runner starts from a stop and increases his speed until crossing the finish line.
( x ) During a 1500 meter race, the runner makes several laps around the track at a constant speed.
( x ) During an out-and-back 10 K race, the runner turns around at the midpoint, maintaining a constant speed throughout the turn.

In all cases above, the runner accelerates because his or her velocity changes. In the first example, the speed changes; in the last two examples the speed is constant but the direction changes.

We can see some differences between the terminology in physics vs. our everyday world ("acceleration" in this case). For example, if you start a car and hit the gas, you woud say that you and the car are accelerating (same in the language of physics). However (before taking this course!) you would be unlikey to say that your car accelerated if you went around a wide bend in the road at constant speed.

Since the slope of velocity of the runner vs. time (Figure 1.3) is clearly different for early vs. later times in the run, this shows that the acceleration is different. Do you think a change in acceleration during a race for a sprinter is "normal"? Maybe you could analyze some more runs and races and find out!

Now we'll have the computer find the acceleration by doing a curve fit to the distance vs. time curve. The computer fits a curve to the distance vs. time data and figures out the acceleration from that. Note that the SI unit of acceleration is "meters per second squared" ($m/s^2$). We'll concentrate on the first 2 seconds of the race when it looks like the acceleration was fairly constant and greater than for later times.

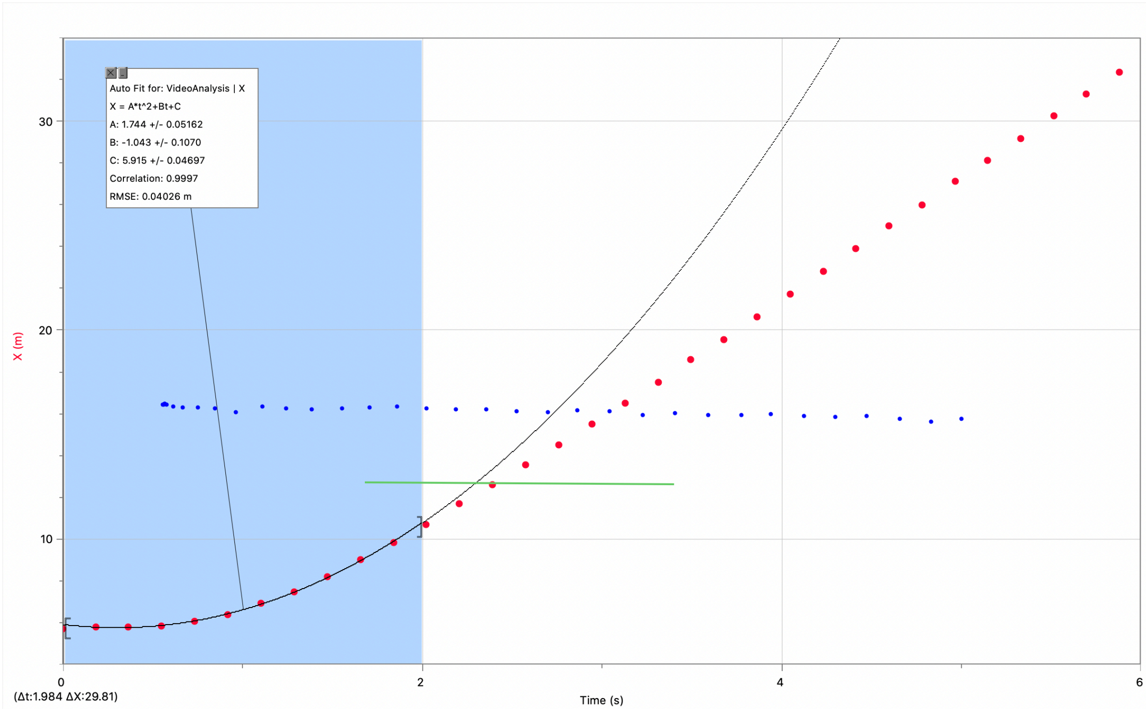



FIGURE 1.4: Plot of Position vs. Time taken from the digitization of VIDEO 1.7 with a quadratic fit to the data for the 1st 2 seconds

The (quadratic) fit that the computer used is a pretty good one (the solid curve which is the fit is pretty close to the data). This confirms that the acceleration is fairly constant over this time interval. The acceleration from the fit is ~3.5 m/s$^2$ (the acceleration is given by twice the "A" parameter in the fit). Now is this a large acceleration or not? We'll get some feeling for this from the results of the next section. (For the later part of the run, a similar computer analysis yielded an acceleration of 0.20 m/s$^2$. This makes sense as you can see from Figure 1.3 that the change in velocity vs. time was a lot less in the second part of the run.)

Just as the slope of a plot of distance vs. time gives the speed/velocity, <u>the slope of a velocity vs. time plot gives the acceleration</u>. In equation form, the acceleration is related to the velocity by:

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time}} \qquad \text{Equation 1.2}$$

So we could have gotten an estimate of the acceleration for early and later times by measuring the slopes in Figure 1.3. If you do that, do you come up with similar answers to the computer fits? I hope so!

For situations that are not quite so simple, physicists use "kinematic equations" that relate distance (technically "displacement" in physics), velocity, acceleration, and time assuming that the acceleration is constant at least over some time interval. They are very useful in analyzing a number of sports and other physical situations involving motion, but that is beyond what we need for this book. We'll let the computer do the harder calculating for us.

# 1.4: Free Fall

All the examples of one-dimensional motion we analyzed in the previous sections involved one dimensional *horizontal* motion. But many sports involve motion in the vertical direction as well. This may involve a projectile (baseball, football, volleyball, tennis ball, shot put, discus, ...) or an athlete (pole vault, high jump, long jump, gymnastics ,...). How is vertical motion different from horizontal motion (from a physics point of view), or is it?

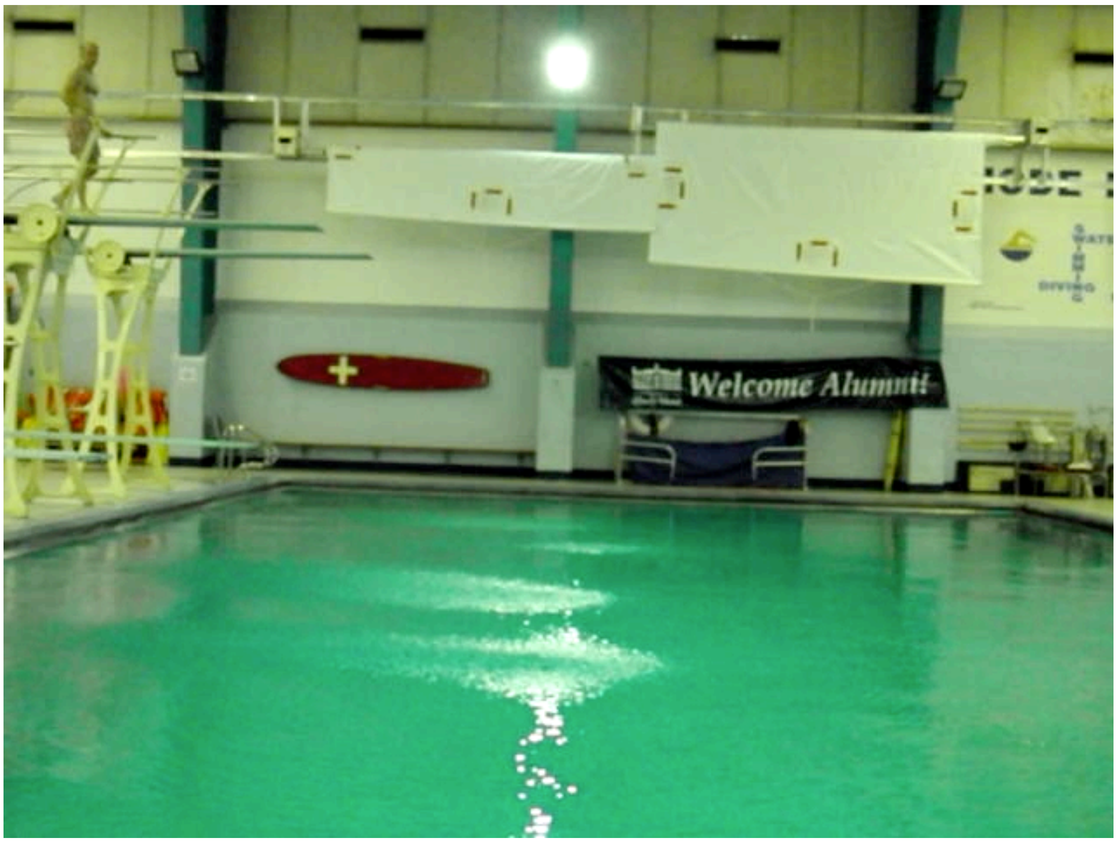
Sticking with one-dimensional motion, let's take a look at an example where the motion is (almost) vertical and (almost) one-dimensional: platform diving. (Can you think of any other sports or athletic activities that involve one-dimensional vertical motion?)

Click on the link for VIDEO 1.8 and watch a dive by Olympic Gold medalist, Greg Louganis.


VIDEO 1.8: Champion Diver Greg Louganis at the 1984 Summer Olympics

[https://digitalcommons.uri.edu/physicsofsports/8/](https://digitalcommons.uri.edu/physicsofsports/8/)

Now we'll digitize a "dive" (jump) by me standing in for Greg. (Select and watch VIDEO 1.9.) Similar to the analysis I did of the sprint, I advance the diver frame-by-frame, placing the cursor and clicking on the waist area of the diver (me) until I have run through the points of the jump (when I start to enter the water). (Why do I stop the analysis when the diver enters the water? What will be different?)




VIDEO 1.9: D. Heskett jumps off a diving board.

https://digitalcommons.uri.edu/physicsofsports/9/

My analysis of the jump is shown below. Similar to when we analyzed the sprint, you can see that the distance between time points increases (in a downward direction in this case) indicating that the speed is increasing. This makes sense as I started from rest so my speed was bound to increase.

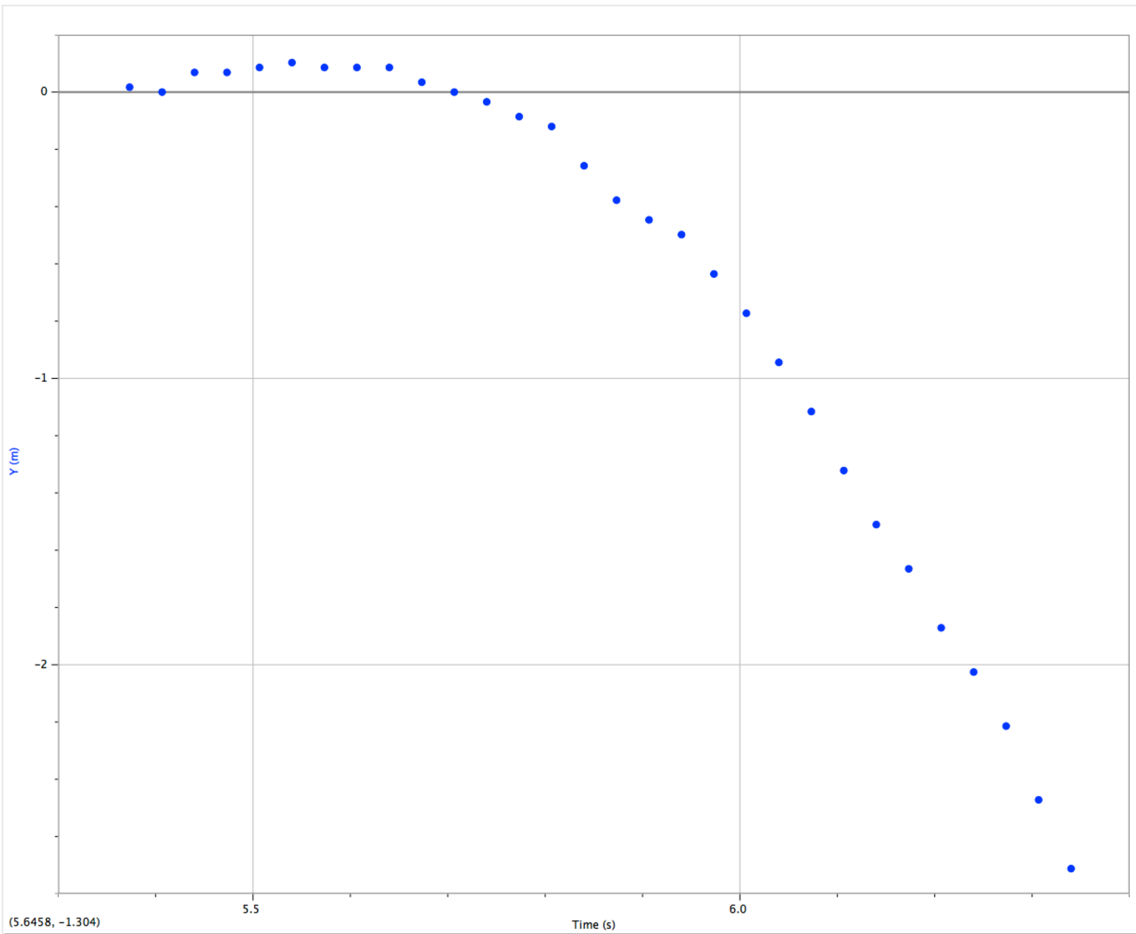



FIGURE 1.6: Plot of Position vs. Time taken from the author's digitization of the previous diving video

Now we let the computer do the work of computing the instantaneous velocity (and speed).

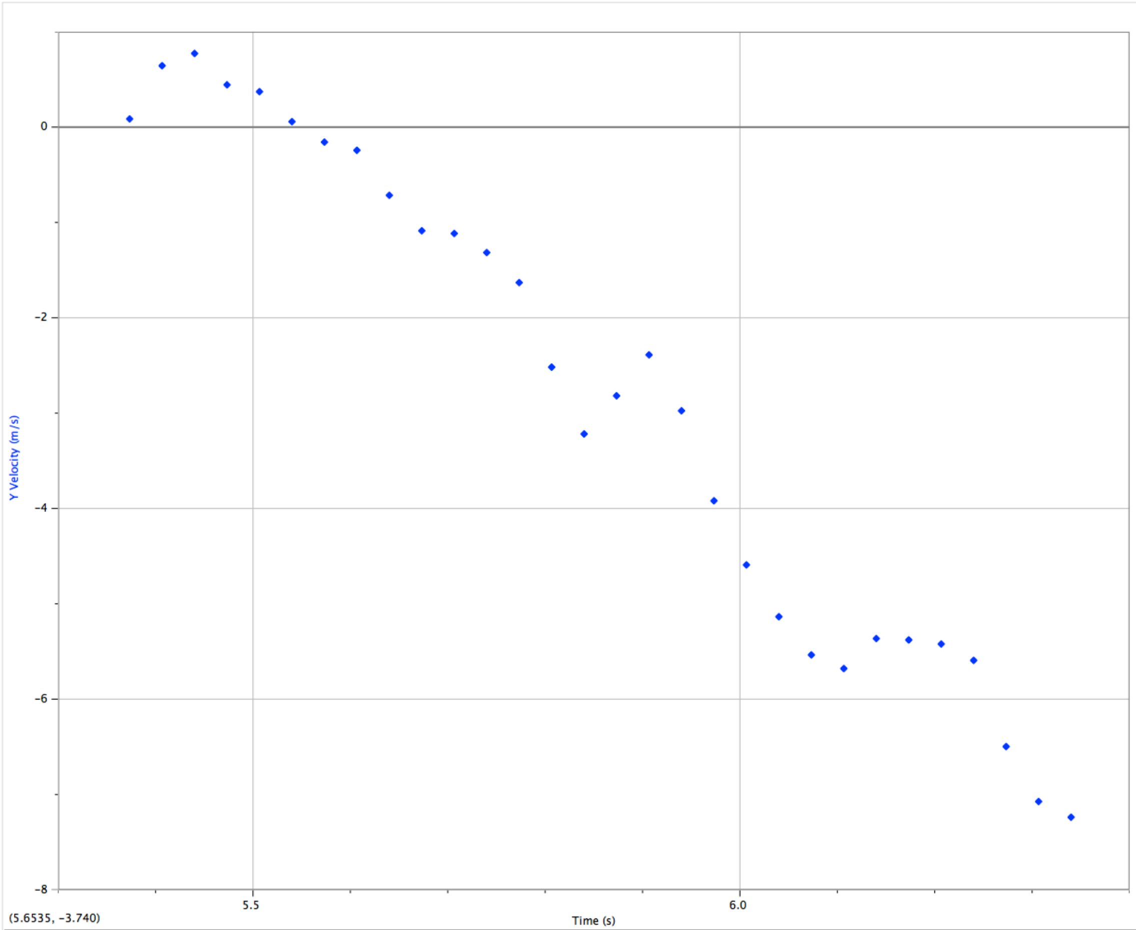



FIGURE 1.7: Plot of Velocity vs. Time taken from the author's digitization of the previous diving video

QUIZ 1.19

What can we say about the speed (the <u>magnitude</u> of the velocity) from the velocity vs. time curve?

( ) The speed is constant for all times.
( x ) The speed is increasing for all times.
( ) The speed is decreasing for all times.

From the plot we can see that the speed is increasing with time (though the plot shows that the velocity is getting more negative because we had chosen "up" to be the positive direction). The plot of speed/velocity vs. time is fairly linear (more or less a straight line). What does this tell us about the acceleration of the diver?

QUIZ 1.20

What can we conclude from this plot about the acceleration of the diver?

| | |
|---|---|
| ( ) | The acceleration is zero. |
| ( x ) | The acceleration is fairly constant. |
| ( ) | The acceleration is decreasing. |
| ( ) | The acceleration is increasing. |

Since the velocity steps are fairly constant - the plot is linear, this means that the acceleration appears to be fairly constant. Let's find out the value of the acceleration by having the computer carry out a fit to the earlier distance vs. time curve (Figure 1.6).

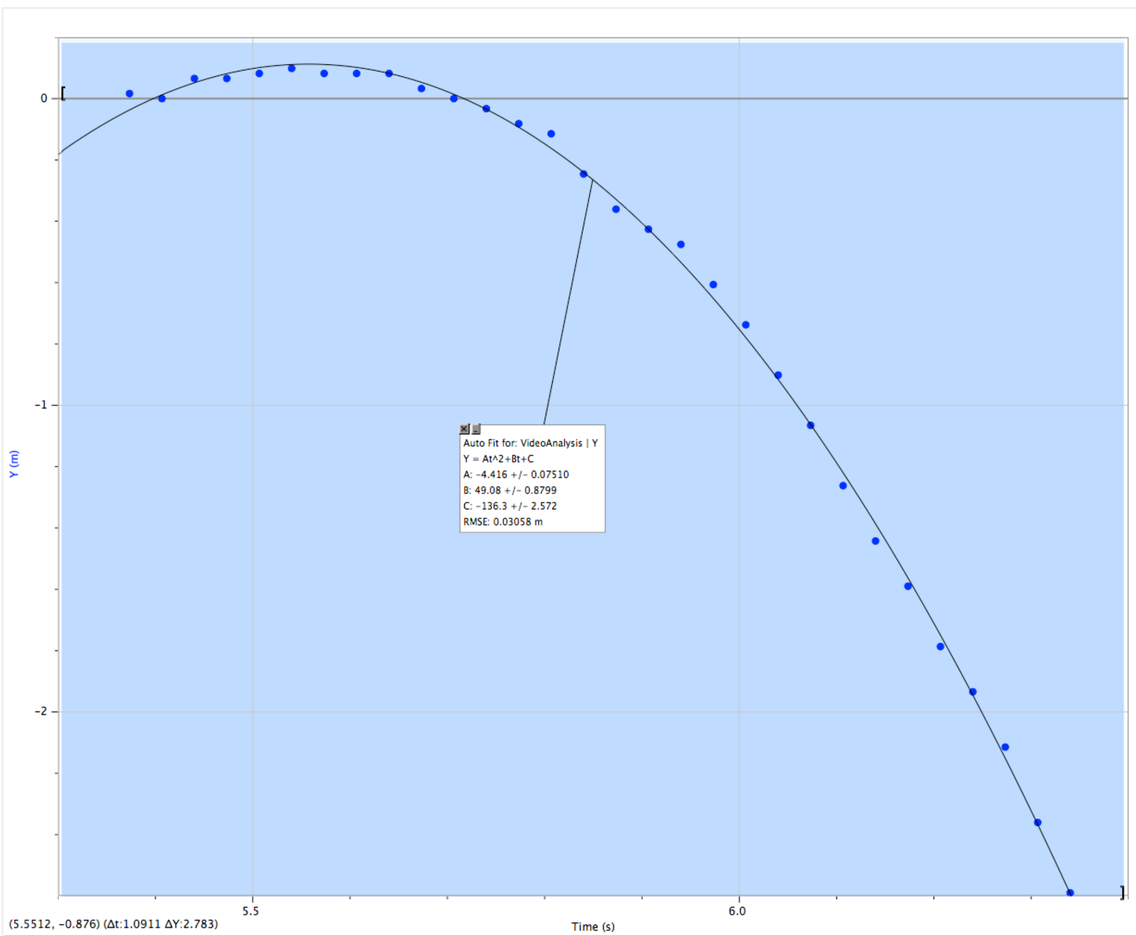



FIGURE 1.9: Curve Fit to Distance vs. Time taken from the author's digitization of the previous diving video

This plot shows that the acceleration is fairly constant, as we had already concluded. Again, the fit is a good one. This type of curve is called a "parabola". The value of the acceleration is approximately 9 m/s$^2$ (that is twice the "A" parameter in the fit). This is the acceleration produced by gravity and is often called "little g" ($g$). The standard measured value on the Earth's surface is 9.81 m/s$^2$, (10 m/s$^2$ is close enough for this course), so my measurements and analysis were close but on the low side.

The fact that the acceleration is constant and approximately equal to $g$ indicates that gravity is most important in determining the motion of the diver. You know gravity had to be important as what would happen if a diver jumped off a platform in deep space (hard to arrange!) where the effects of gravity are negligible?

Let's consider what an acceleration of $g$ = 10 m/s$^2$ means. Acceleration is the change in speed vs. time so this value of acceleration means speed (or velocity) increases by 10 meters per second (approximately 2.2 mph) every second. When I jumped, my speed was 0 at the beginning, 10 meters per second after the first second, 20 meters per second after the 2nd second (if I had stayed in the air that long), etc.

QUIZ 1.21

If a diver stays in the air long enough, what would be his/her approximate speed after four seconds?

( ) 4 miles per hour
( ) 6 miles per hour
( x) 9 miles per hour
( ) 12 miles per hour

Now we have an acceleration we are familiar with ($g$ = 10 m/s$^2$) so we have something to compare to a runner's acceleration. The acceleration of the runner in VIDEO 1.7 was ~3.5 m/s$^2$ for the first 2 seconds, ~1/3 of free fall acceleration. We'll talk more about Bolt' acceleration later in the book.

In the next chapter, we'll apply many of these ideas to two-dimensional motion.

## Chapter 1 Homework

### Questions

1. What is the SI unit of length?

(A) centimeter
(B) foot
(C) meter
(D) kilometer

Answer: (C)

2. What is the SI unit of length?

______________

Answer: meter

3. What is the SI unit of velocity?

(A) mile per hour
(B) kilometer per hour
(C) meter per hour
(D) meter per second
(E) feet per second

Answer: (D)

4. Compare the average speed of a runner in a 200 meter race to the average speed of a runner in a 1500 meter race.

(A) The average speeds will be about the same.
(B) The average speed in the 200 meter race will be greater.
(C) The average speed in the 200 meter race will be less.

Answer: (B)

5. Compare the average speed of a runner in a 200 meter race to the average speed of a swimmer in a 200 meter race.

(A) The average speeds will be about the same.
(B) The average speed of the runner will be greater.
(C) The average speed of the swimmer will be greater.

Answer: (B)

6. Rank the top speeds of the projectiles in the situations listed below:

A Football pass
B Hockey slap shot
C Baseball hit by a bat
D Hurling sliotar
E Cricket ball

Answer: E > B > C > D > A

7. Rank the average speeds of athletes in the events listed below:

A 100 meter wheelchair race
B pole vault approach
C 4 man bobsled race
D 200 meter time trails in cycling
E 500 meter short track speed skating

Answer: D > E > A > B > C

8. For the following situations, place a check if the speed changes and a check if the velocity changes:

| Sports Activity | Speed Changes? | Velocity Changes? |
|---|---|---|
| a. Diver jumping off diving board | x | x |

| | | |
|---|---|---|
| b. Bobsled sliding down a track | x | x |
| c. Tether ball spinning around a pole at constant speed | | x |
| d. Cyclist riding around a circular track at 25 mph | | x |

9. From the list below, choose the <u>two</u> best examples of approximately one-dimensional motion:

A High Jump
B Bungee jump
C Golf shot
D Discus throw
E Trampoline gymnastics

<u>Answer</u>: B and E

10. Cesar Cielo from Brazil holds the world record (set in 2009) in the 50 meter freestyle swimming event with an average speed of ~2.3 meters per second. This race (the "long course") involves swimming one length of the pool. Including the start, was Cielo's speed constant throughout the race?

(A) Yes
(B) No
(C) Not enough information is given

<u>Answer</u>: (B)

11. Michael Phelps set a world record in the 100 meter butterfly swimming event in 2009 with an average speed of ~2.0 meters per second. This race (the "long course") involves swimming two lengths of the pool. If we ignore the start of the race and concentrate on the rest of it, was Phelp's speed constant throughout the remainder of the race?

(A) Yes
(B) No
(C) Not enough information is given

<u>Answer</u>: (B)

12. You are told that a bicycle rider accelerates during one segment of her event. What can we say about the a. speed, b. velocity, and c. direction of the cyclist?

a.
(A) The speed is constant.
(B) The speed changes
(C) Not enough information is given.

<u>Answer</u>: (C)

b.
(A) The velocity is constant.
(B) The velocity changes
(C) Not enough information is given.

<u>Answer</u>: (B)

c.
(A) The direction is constant.
(B) The direction changes
(C) Not enough information is given.

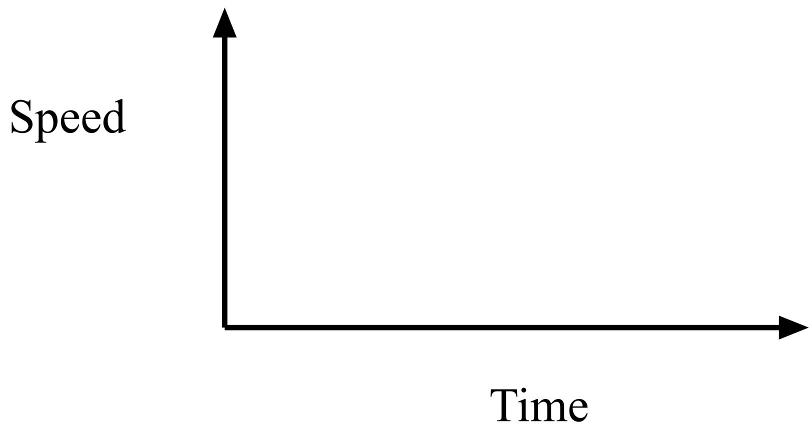
<u>Answer</u>: (C)

13. A speed skater rounds a turn on an oval speed skating track at constant speed.
a. What can we say about the velocity of the skater?
(A) The velocity was constant.
(B) The velocity was not constant

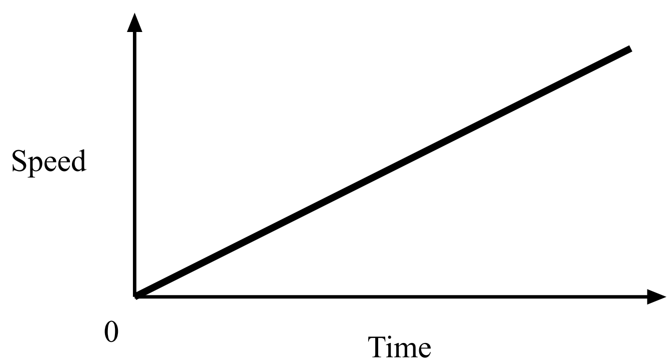
b. Did the skater accelerate?
(A) Yes
(B) No

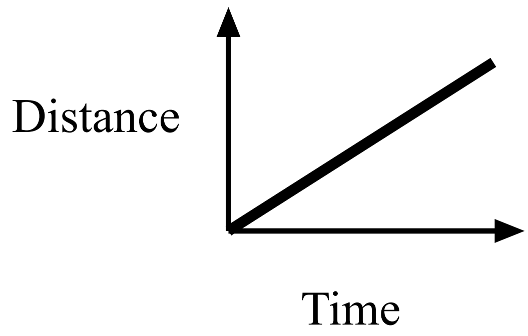
<u>Answers</u>: (B), (A)

14. Assuming a bike rider starts from rest and travels with constant acceleration, sketch a plot of the speed of the bicycle as a function of time on the plot below.




Answer:

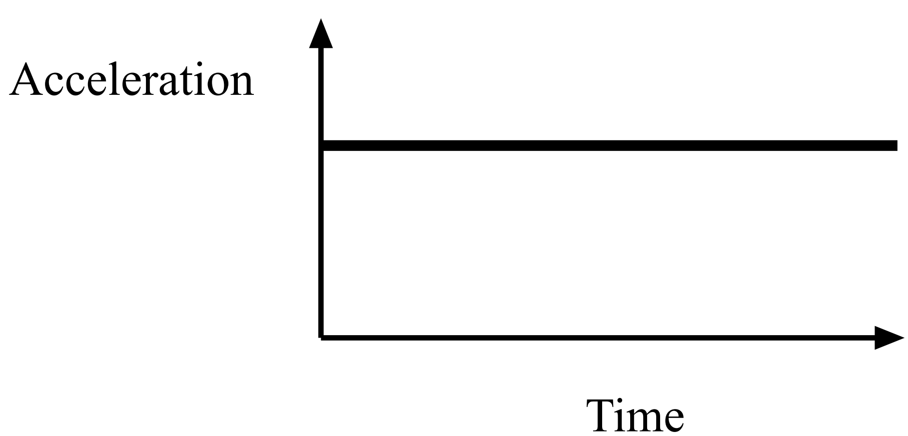





15. The graph above represents a plot of distance vs. time for a bike rider. What can we say about the acceleration and speed of the cyclist vs. time?

(A) The acceleration and speed are both increasing.
(B) The acceleration and speed are both 0.
(C) The acceleration is 0; the speed is increasing.
(D) The acceleration is increasing; the speed is 0.
(E) The acceleration is increasing; the speed is constant.
(F) The acceleration is constant; the speed is increasing.
(G) None of the above.

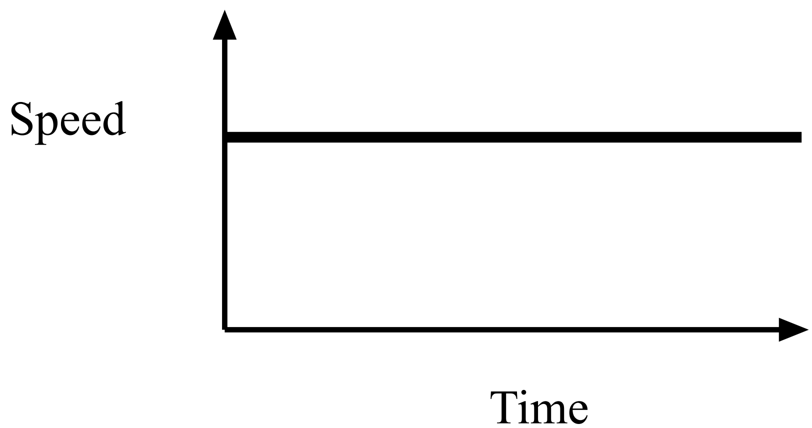
Answer: (G)



16. The graph above represents a plot of acceleration vs. time for a runner. What can we say about the distance traveled and speed of the runner vs. time?

(A) The distance and speed are both increasing.
(B) The distance and speed are both 0.
(C) The distance is 0; the speed is increasing.
(D) The distance is increasing; the speed is 0.
(E) The distance is increasing; the speed is constant.
(F) The distance is constant; the speed is increasing.

Answer: (A)




17. The graph above represents a plot of speed vs. time for a swimmer. What can we say about the distance traveled and the acceleration of the swimmer vs. time?

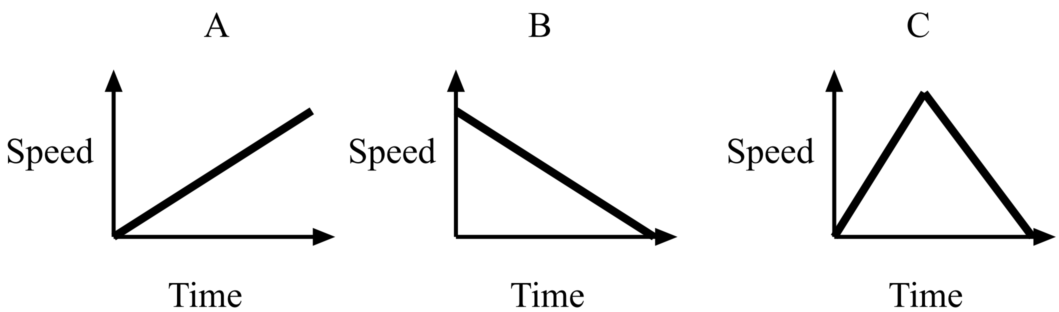
(A) The distance and acceleration are both increasing.
(B) The distance and acceleration are both 0.
(C) The distance is 0; the acceleration is increasing.
(D) The distance is increasing; the acceleration is 0.
(E) The distance is increasing; the acceleration is constant.
(F) The distance is constant; the acceleration is increasing.

Answer: (D)

18. A diver steps off a diving board in deep space. What happens?

(A) The diver moves "down" in the same direction he would on Earth.
(B) The diver moves "up" in the opposite direction as he would on Earth.
(C) The diver moves neither "up" nor "down".

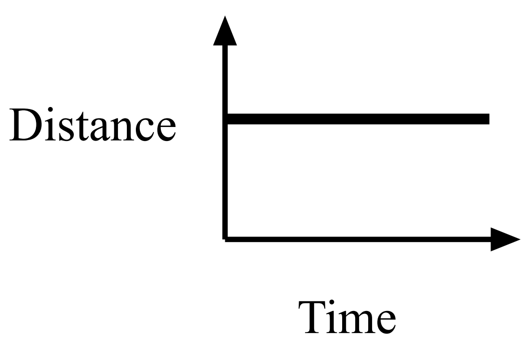
Answer: (C)




19. A sprinter runs a 100 meter race with constant acceleration. Which plot best depicts the runner's speed vs. time during the race?

________

Answer: (A)

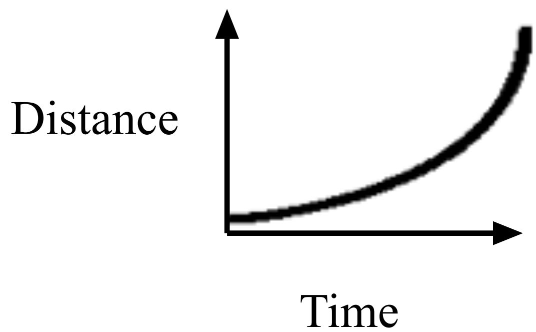



20. The graph above represents a plot of distance vs. time for a swimmer for a portion of her event. What can we say about the acceleration and speed of the swimmer vs. time?

(A) The acceleration and speed are both increasing.
(B) The acceleration and speed are both 0.
(C) The acceleration is 0; the speed is increasing.

(D) The acceleration is increasing; the speed is 0.
(E) The acceleration is increasing; the speed is constant.
(F) The acceleration is constant; the speed is increasing.

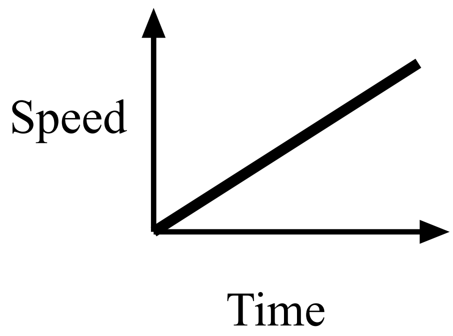
Answer: (B)




21. The graph above represents a plot of distance vs. time for a runner. What can we say about the acceleration and speed of the runner vs. time? (Assume the plot is a parabola.)

(A) The acceleration and speed are both increasing.
(B) The acceleration and speed are both 0.
(C) The acceleration is 0; the speed is increasing.
(D) The acceleration is increasing; the speed is 0.
(E) The acceleration is increasing; the speed is constant.
(F) The acceleration is constant; the speed is increasing.

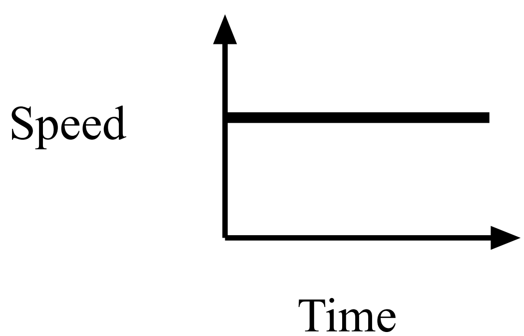
Answer: (F)




22. The graph above represents a plot of speed vs. time for a swimmer. What can we say about the acceleration and speed of the swimmer vs. time?

(A) The acceleration and speed are both increasing.
(B) The acceleration and speed are both 0.
(C) The acceleration is 0; the speed is increasing.
(D) The acceleration is increasing; the speed is 0.
(E) The acceleration is increasing; the speed is constant.
(F) The acceleration is constant; the speed is increasing.

Answer: (F)

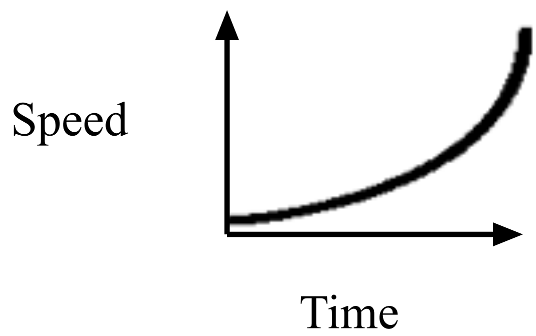



23. The graph above represents a plot of speed vs. time for a runner. What can we say about the acceleration and speed of the runner vs. time?

(A) The acceleration and speed are both increasing.
(B) The acceleration and speed are both 0.
(C) The acceleration is 0; the speed is increasing.

(D) The acceleration is increasing; the speed is 0.
(E) The acceleration is 0; the speed is constant.
(F) The acceleration is constant; the speed is increasing.

Answer: (E)




24. The graph above represents a plot of speed vs. time for a runner. What can we say about the acceleration and speed of the runner vs. time?

(A) The acceleration and speed are both increasing.
(B) The acceleration and speed are both 0.
(C) The acceleration is 0; the speed is increasing.
(D) The acceleration is increasing; the speed is 0.
(E) The acceleration is increasing; the speed is constant.
(F) The acceleration is constant; the speed is increasing.

Answer: (A)

25. A diver steps off a 10 meter platform. At what point in the dive is his speed the lowest and highest?

(A) Lowest as he steps off the platform; highest as he enters the water.
(B) Highest as he steps off the platform; lowest as he enters the water.
(C) Lowest and highest in the middle of the dive.

Answer: (A)

26. A diver jumps up from a 3 meter springboard. At what point in the dive is her speed the lowest and highest?

(A) Lowest as she jumps off the board; highest as she enters the water.
(B) Highest as she jumps off the board; lowest as she enters the water.
(C) Lowest at the top of her dive; highest as she enters the water.
(D) Highest at the top of her dive; lowest as she enters the water.
(E) Lowest and highest in the middle of the dive.

Answer: (C)

27. A shot is thrown straight up in the air. At what point in the trajectory is the speed the lowest and highest?

(A) Lowest as the shot leaves the athlete's hand; highest when it hits the ground.
(B) Highest as the shot leaves the athlete's hand; lowest when it hits the ground.
(C) Lowest as the shot leaves the athlete's hand; highest when it reaches its highest point.
(D) Highest as the shot leaves the athlete's hand; lowest when it reaches its highest point.
(E) Highest when the shot hits the ground; lowest when it reaches its highest point.
(F) Lowest when the shot hits the ground; highest when it reaches its highest point.

Answer: (E)

28. Bolt's average speed for his 200 meter race in the 2008 Summer Olympics was slightly greater than for his 100 meter race. Can you suggest a reason for this?

29. In our analysis of Ichiro Suzuki's base-stealing video, why would 85 feet be a better choice of distance to calculate average speed than the 90 feet separating the bases?

30. What's hurling? What's a sliotar?

31. Name some sports in which the speed of a sports object is constant (and moving!).

32. Name some sports in which the sports object does not change direction.

33. Besides diving, what other sports involve mostly one-dimensional vertical motion?

34. In the analysis of the dive video, you were instructed to stop the digitization once the diver entered the water. Explain why.

## Exercises

1. How many centimeters are there in a meter?

(A) 0.1
(B) 10
(C) 100
(D) 1000

Answer: (B)

2. How many centimeters are there in a millimeter?

(A) 0.1
(B) 10
(C) 100
(D) 1000

Answer: (A)

3. You ran a 5K (5 kilometer) race. Approximately how many miles did you run?

(A) 1 mile
(B) 2 miles
(C) 3 miles
(D) 4 miles

Answer: (C)

4. A football field is 300 feet long. Approximately how many meters is that?

(A) 50 meters
(B) 100 meters
(C) 150 meters
(D) 200 meters
(E) 300 meters

Answer: (B)

5. Choose the approximate distance covered in a 400 meter race:

(A) 400 feet
(B) 800 feet
(C) 1300 feet

(D) 1600 feet
(E) 2000 feet

Answer: C

6. Choose the approximate distance covered in a 400 meter race:

(A) 140 yards
(B) 240 yards
(C) 340 yards
(D) 440 yards
(E) 540 yards

Answer: C

7. A runner completes a 200 meter race in 20 seconds. What was the average speed of the runner?

_________________ meters per second

Answer: 10 m/s

8. A runner completes a 200 meter race in 20 seconds. What was the average speed of the runner?

_________________ miles per hour

Answer: 22.4 miles per hour

9. A runner completes a 400 meter race with an average speed of 20 m/s. How long did it take the runner to finish the race?

_________________ seconds

Answer: 20 seconds

10. A ball is traveling with a speed of 60 mph. What is the approximate speed?

(A) 15 meters per second
(B) 25 meters per second
(C) 35 meters per second
(D) 45 meters per second
(E) 55 meters per second

Answer: B

11. Find the speed of a 90.0 mph fast ball in m/s.

________________ meters per second

Answer: 40.2 meters per second

12. The women's 500 meter speed skating record (Jenny Wolf from Germany) was completed with an average speed of 13.5 meters per second. How long did it take the athlete to complete the race?

________________ seconds

Answer: 37 seconds

13. A runner runs a 5 kilometer race in 30 minutes. Find the average speed in the following units:

a. ___________ kilometers per hour

b. ___________ miles per hour

c. ___________ meters per second

Answers:
a. 10 kilometers per hour
b. 6.2 miles per hour
c. 2.8 meters per second

14. Cesar Cielo from Brazil holds the world record (set in 2009) in the 50 meter freestyle swimming event ("long course") with an average speed of ~2.3 meters per second. How long did it take Cielo to complete this race?

________________ seconds

Answer: 22 seconds

15. A ball has been dropping from rest in free fall (no air resistance) for 3 seconds. What is the speed and the acceleration of the ball?

________ meters per second

___________ $m/s^2$

Answers: 30 meters per second, 10 $m/s^2$

16. In his 100 meter Olympic race, Bolt's average acceleration was ~2.1 $m/s^2$. What was his approximate speed after 3.5 seconds?

________ meters per second

Answer: 7.35 meters per second

17. A shot put is thrown straight up into the air. Ignoring air resistance, what are the velocity and acceleration at the highest point?

________ meters per second

___________ $m/s^2$

Answers: 0, 10 $m/s^2$

18. A U.S. team won the gold medal in the 4 man bobsled race in the 2010 Winter Olympics with a total time over 4 runs of 3 minutes, 24.46 seconds. With a course length of 1450 meters, this turns out to be an average acceleration of ~1.1 $m/s^2$. What would be

the approximate speed of the bobsled after a run time of 50 seconds (near the end of the run)?

________ meters per second

Answer: 55 meters per second

19. Carlo Janka from Switzerland won the gold medal in the giant slalom skiing race in the 2010 Winter Olympics with an average time (from 2 runs) of 79 seconds over a course length of 1512 meters. With a speed of 38 meters per second near the bottom of the run, find Janka's average acceleration?

___________ $m/s^2$

Answer: 0.48 $m/s^2$

20. You throw a shot straight up into the air for 2 seconds, at which time it reaches its highest point. Ignoring air resistance, what are the speed and acceleration of the shot at the highest point? (Take "up" as the positive direction.)

| | Speed | Acceleration |
|---|---|---|
| (A) | 0 | 0 |
| (B) | 0 | 10 $m/s^2$ |
| (C) | 10 m/s | 0 |
| (D) | 10 m/s | 10 $m/s^2$ |
| (E) | 0 | -10 $m/s^2$ |
| (F) | -10 m/s | -10 $m/s^2$ |

Answer: (E)

21. You throw a shot straight up into the air with an initial speed of 20 meters per second. Ignoring air resistance, after one second what are the speed and acceleration of the shot? (Take "up" as the positive direction.)

| | Speed | Acceleration |
|---|---|---|
| (A) | 20 m/s | 10 m/s$^2$ |
| (B) | 10 m/s | 10 m/s$^2$ |
| (C) | 10 m/s | 20 m/s$^2$ |
| (D) | 20 m/s | 20 m/s$^2$ |

Answer: (C)

22. You throw a shot straight down from the top of a cliff with an initial speed of 20 meters per second. Ignoring air resistance, after one second what are the speed and acceleration of the shot put? (Take "down" as the positive direction.)

| | Speed | Acceleration |
|---|---|---|
| (A) | 10 m/s | 10 m/s$^2$ |
| (B) | 30 m/s | 10 m/s$^2$ |
| (C) | 20 m/s | 10 m/s$^2$ |
| (D) | 10 m/s | 20 m/s$^2$ |
| (E) | 20 m/s | 20 m/s$^2$ |
| (F) | 30 m/s | 10 m/s$^2$ |
| (G) | 10 m/s | 30 m/s$^2$ |
| (H) | 30 m/s | 30 m/s$^2$ |

Answer: (B)

23. A ball has been dropping from rest in free fall (no air resistance) for 3 seconds. What is the approximate speed of the ball and the approximate acceleration? (Take "down" as the positive direction.)

| | Speed | Acceleration |
|---|---|---|
| (A) | 10 m/s | 10 m/s$^2$ |
| (B) | 20 m/s | 10 m/s$^2$ |
| (C) | 10 m/s | 20 m/s$^2$ |
| (D) | 20 m/s | 20 m/s$^2$ |
| (E) | 30 m/s | 10 m/s$^2$ |
| (F) | 10 m/s | 30 m/s$^2$ |
| (G) | 30 m/s | 20 m/s$^2$ |

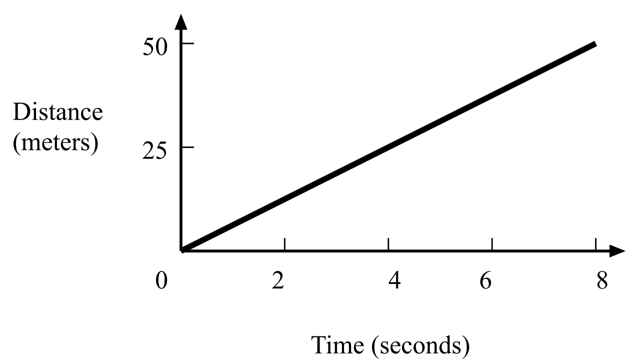
Answer: (E)

24. You throw a shot straight up into the air with an initial speed of 40 meters per second. Ignoring air resistance, what are the speed and acceleration of the shot after five seconds? (Take "up" as the positive direction.)

| | Speed | Acceleration |
|---|---|---|
| (A) | 20 m/s | 10 m/s$^2$ |
| (B) | 10 m/s | 10 m/s$^2$ |
| (C) | 10 m/s | 20 m/s$^2$ |
| (D) | 30 m/s | 10 m/s$^2$ |
| (D) | 30 m/s | 20 m/s$^2$ |
| (D) | 50 m/s | 10 m/s$^2$ |

Answer: (B)

25. The plot below depicts the distance vs. time for a sprinter running the 50 meter dash. From the graph, find the average speed of the sprinter.




_________________ meters per second

Answer: 6.25 meters per second

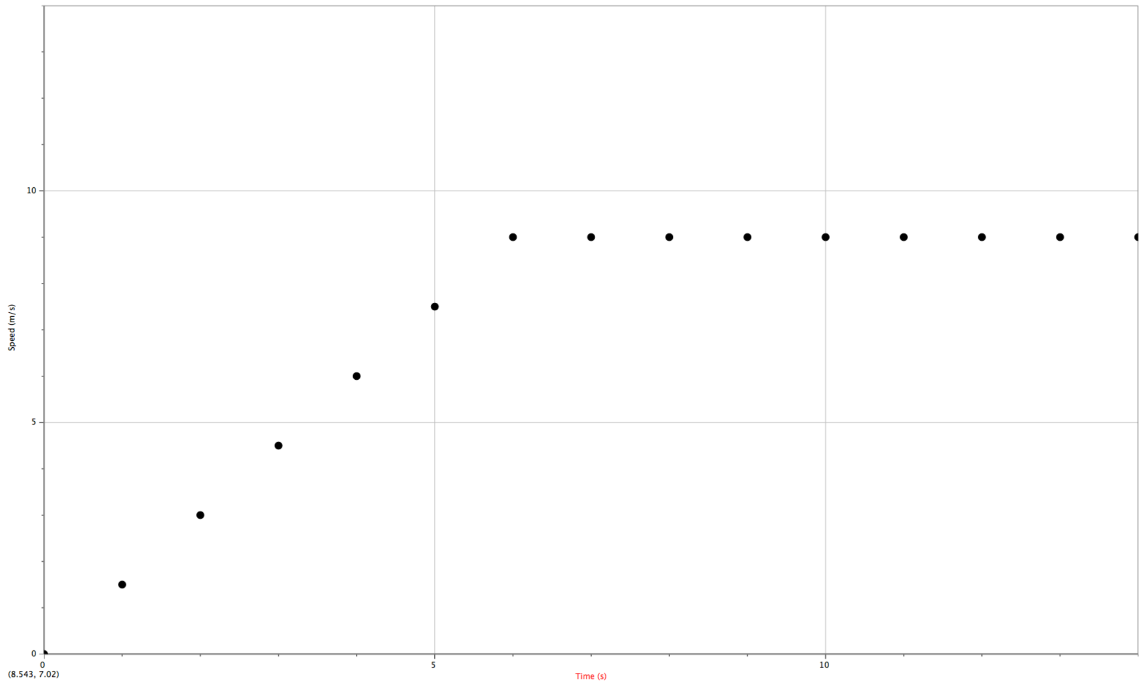
26. The data below depicts the speed vs. time for a sprinter running a 100 meter dash.
a. Plot the data with speed on the vertical axis and time on the horizontal axis.

b. From the graph, find the average acceleration of the sprinter for the first part of the race and the last part of the race.

| Speed (m/s) | Time (s) |
|---|---|
| 0 | 0 |
| 1.5 | 1 |
| 3.0 | 2 |
| 4.5 | 3 |
| 6.0 | 4 |
| 7.5 | 5 |
| 9.0 | 6 |
| 9.0 | 7 |
| 9.0 | 8 |
| 9.0 | 9 |
| 9.0 | 10 |
| 9.0 | 11 |
| 9.0 | 12 |

a.


Answer:




b.

___________ $m/s^2$

___________ $m/s^2$

Answers: 1.5 $m/s^2$ , 0

27. The full length of a regulation badminton court is 44 feet. If a player stands at the net and smashes a badminton shuttlecock with a speed of 200 miles per hour, approximately how long does it take the shuttlecock to reach the end of the other side of the court?

________________ second

Answer: 0.075 second

28. A home run in baseball travels 400 feet into the stands. If the ball took 3.5 seconds to travel this distance, what was the average speed of the ball?

________________ mph

Answer: 78 mph

29. The 2011 Kentucky Derby was won by the horse "Animal Kingdom" ridden by jockey John Velazquez. The length of the race is 10 furlongs (1.25 miles) and the winning time was 2 minutes and 2.04 seconds. What was the average speed of the horse?

________________ mph

Answer: 36.9 mph

30. The cheetah is the fastest land animal with a top speed in the range of 70 mph. At that speed, how long would it take a cheetah to complete a 100 meter dash (recall that the current world record for humans is Bolt's time of 9.58 seconds set in 2009).

________________ seconds

Answer: 3.2 seconds

# CHAPTER 2: Motion in Two Dimensions


David Ortiz of the Boston Red Sox takes a big swing

https://i.pinimg.com/originals/7a/83/94/7a8394b141ba9e28636b096d9685a007.
jpg


VIDEO 2.1: Walk-off home run by David Ortiz of the Boston Red Sox in Game 4 of the 2004 ACLS

https://digitalcommons.uri.edu/physicsofsports/10/

## 2.1: Horizontal and Vertical Motion

In Chapter 1, we spent quite a few "epages" describing and discussing the physics of motion in one dimension. However most motion in sports, like the David Ortiz home run you just watched (VIDEO 2.1) (a pivotal walk-off home run in the 12th inning of Game 4 of the 2004 American League Championship Series between the Boston Red Sox and the New York Yankees), and certainly most of our activities in the real world involve motion in two or three dimensions. How do we describe this kind of motion (from a physics perspective)? Is it related to what we have already learned? Do we have to start all over again? Fortunately, we do not have to start again but can build on what we have already learned.

Before we can understand the home run in baseball completely (or nearly so), we'll start with something "simpler"- the shot put. Why do you think this is "simpler" to describe and understand? What might be more important in affecting the motion of a baseball than the motion of a shot? (It will take us several chapters before we can fully address this issue.)

Select VIDEO 2.2 and watch an impressive shot put by Olympic gold medalist, Reese Hoffa.

VIDEO 2.2: Reese Hoffa of the U.S. throws the shot put at the 2009, Doha, Qatar, IAAF Qatar Athletic Super Grand Prix.

https://digitalcommons.uri.edu/physicsofsports/11/

Clearly the "shot" travels in two dimensions - up into the air and then down (vertical motion) at the same time as it covers some distance along the ground (horizontal motion). We'll call this path its "trajectory". One of the beautiful things we learn from physics is that is completely correct to analyze these motions (horizontal and vertical) separately and, if necessary, to combine the results of these separate analyses later on. To see how this works we'll first look at the motion of a projectile traveling just in the horizontal direction and just in the vertical direction. We'll put our video analyzing skills to work on these one-dimensional motions, then we'll tackle a true two-dimensional trajectory.

Horizontal motion first - how are we going to do this? There is no easy way on Earth to achieve strict one-dimensional *horizontal* motion through the air. Why not?

QUIZ 2.1

Why can we never get a projectile to travel with just horizontal motion through the air under normal conditions?

( ) The air itself will affect the motion and make it two-dimensional.
( ) Any breeze would change the direction of the projectile.
( x ) The Earth's gravity will change the direction of the projectile.

In deep space we could examine the motion of a projectile without the influence of gravity (though it is not clear in deep space what "horizontal motion" would mean).

So back to the question - how can we at least *approximate* one-dimensional horizontal motion of a shot? Any suggestions? The best I've come up with are: 1. sliding a shot across a flat patch of ice, or 2. rolling a shot on a hard, flat surface such as concrete.

In Chapter 1 we saw that a curling stone will come to rest "on its own" so #1 above may not be the best choice. (Not really "on its own" - which of Newton's Laws applies? See Chapter 4.) We'll try #2. Click on the link for VIDEO 2.3 and watch a lacrosse ball rolling across a tile floor (I didn't have an actual shot handy.). Then we'll use our video skills to digitize the horizontal motion of the ball.

VIDEO 2.3: Lacrosse Ball rolling along the ground-horizontal motion.

https://digitalcommons.uri.edu/physicsofsports/12/

Looking at my analysis below, the plot of position vs. time for the rolling ball is linear, similar in appearance to parts of videos we watched in the last chapter. The linear plot tells us that the increase in distance is the same for the same increase in time.

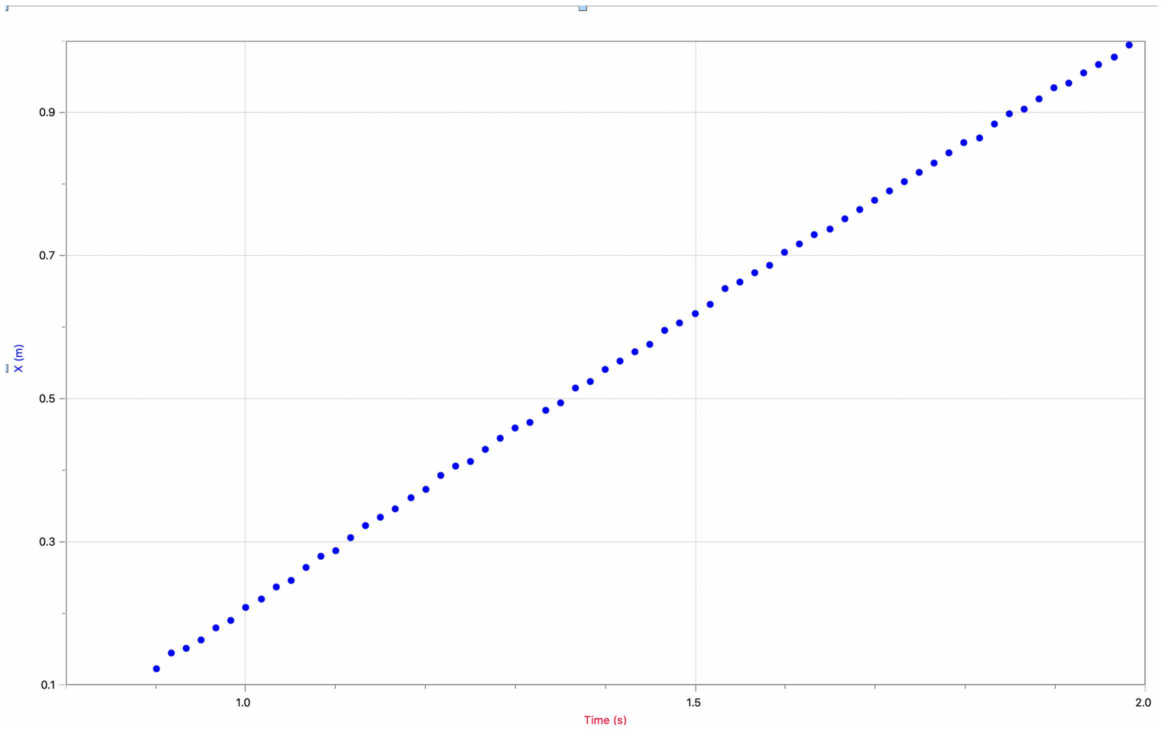



FIGURE 2.1: Author's Rolling Ball digitization

## QUIZ 2.2

What does this plot tell us about the speed (and velocity) of the rolling ball?

( x ) The speed and velocity of the ball are constant.
( ) The speed and velocity of the ball are increasing.
( ) The speed and velocity of the ball are decreasing.

Since the direction did not change and the distance steps are the same, both speed and velocity are (approximately) constant.

Now we will let the computer calculate and plot the instantaneous velocity of the rolling ball versus time.

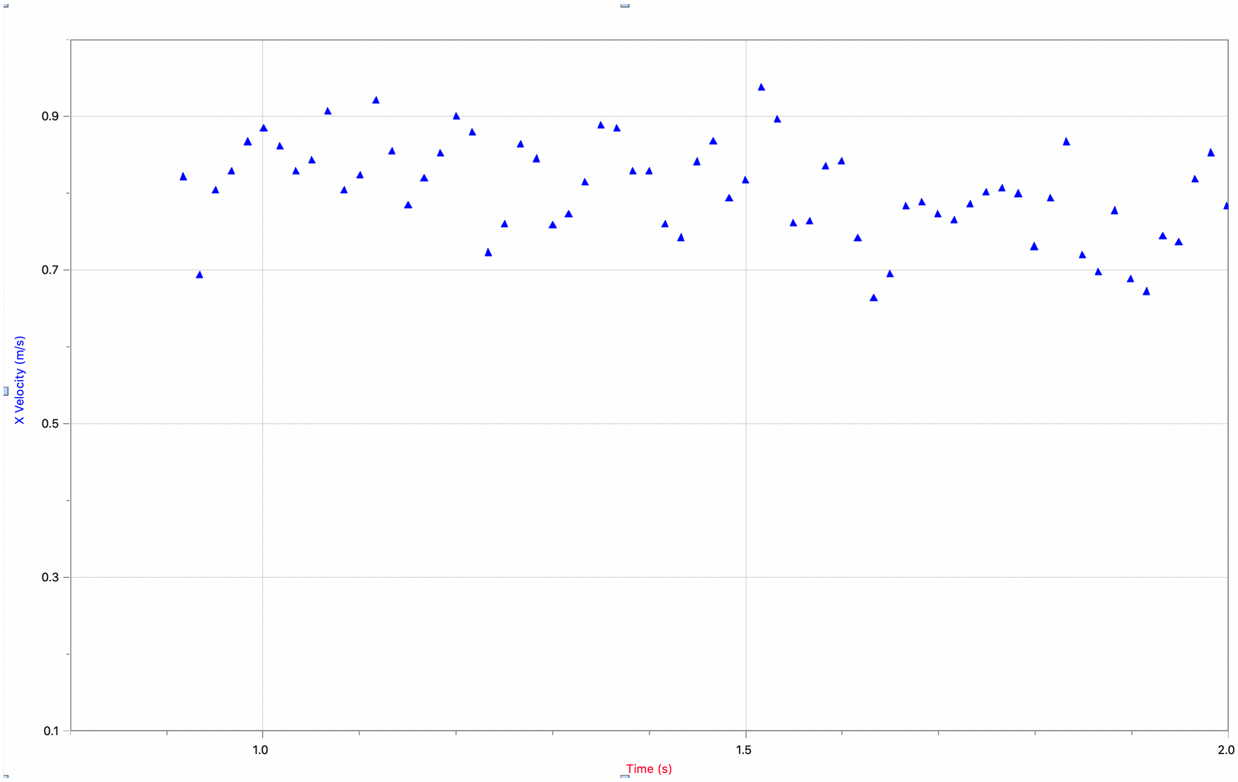



FIGURE 2.2: Velocity vs. time plot of author's rolling ball data

The plot of velocity vs. time is relatively flat which confirms that the speed and velocity are approximately constant (at ~0.85 m/s). (Though it looks like the speed did decrease slightly later in the trajectory. Why?) So what about the acceleration? We learned in the last chapter that constant velocity means zero acceleration, so there is no point in plotting or fitting the curve to examine that.

Now for the vertical motion. We'll shoot a projectile straight up (almost) in the air and analyze that motion. Select the link for VIDEO 2.4.

VIDEO 2.4: Vertical ball shot

https://digitalcommons.uri.edu/physicsofsports/13/

Taking a look at my analysis below, this plot of position vs. time is clearly <u>not</u> linear. As we would expect, the plot tracks the ball as it goes up into the air, then down later, ending "close" to its starting point. In addition, the distance spacing between time intervals is changing, so even when the ball is traveling up or down, the speed/velocity is <u>not</u> constant.

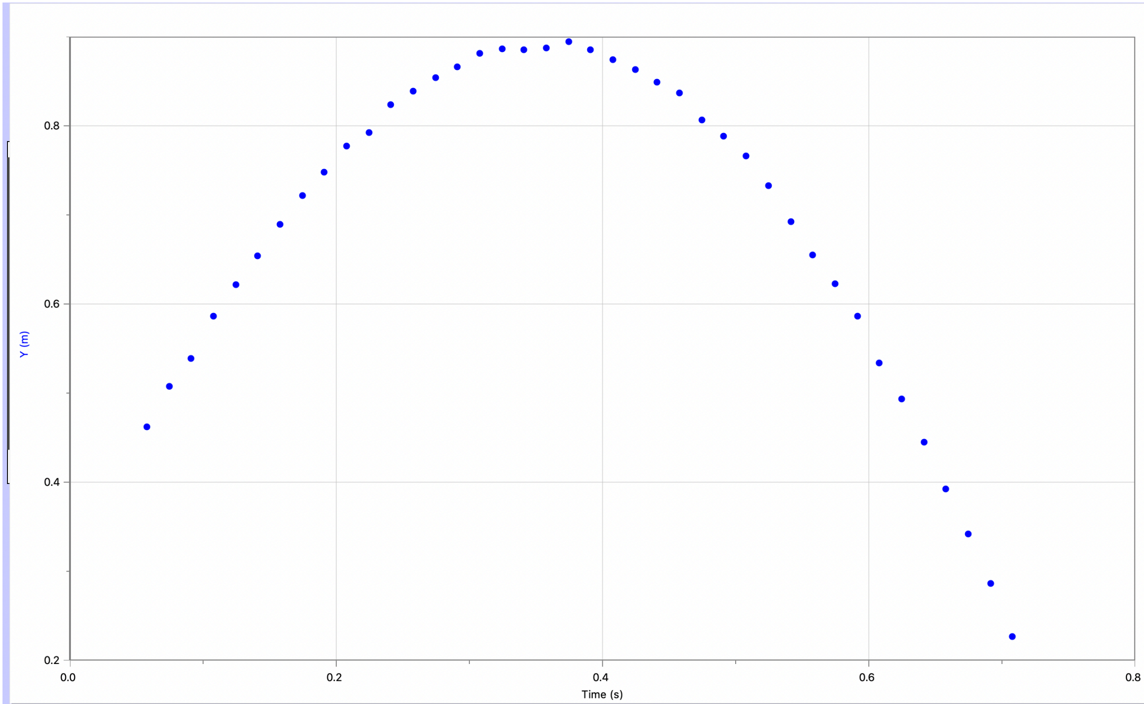



FIGURE 2.3: Vertical ball digitization

QUIZ 2.3

The downward portion of this graph most closely resembles the plot of which sport from the previous chapter?

( ) Yoga instructor's sprint
( ) Portion of 10 K running race
( x ) Author's jump from the diving board

If you compare the second half of the trajectory plotted above to my digitized jump off the diving board plotted in Figure 1.6, you should observe a similar example of free fall as discussed in section 1.4. If we now have the computer fit the data, we can obtain the acceleration of the shot, which should be the acceleration due to gravity, ~10 m/s$^2$. Is it? Let's find out.

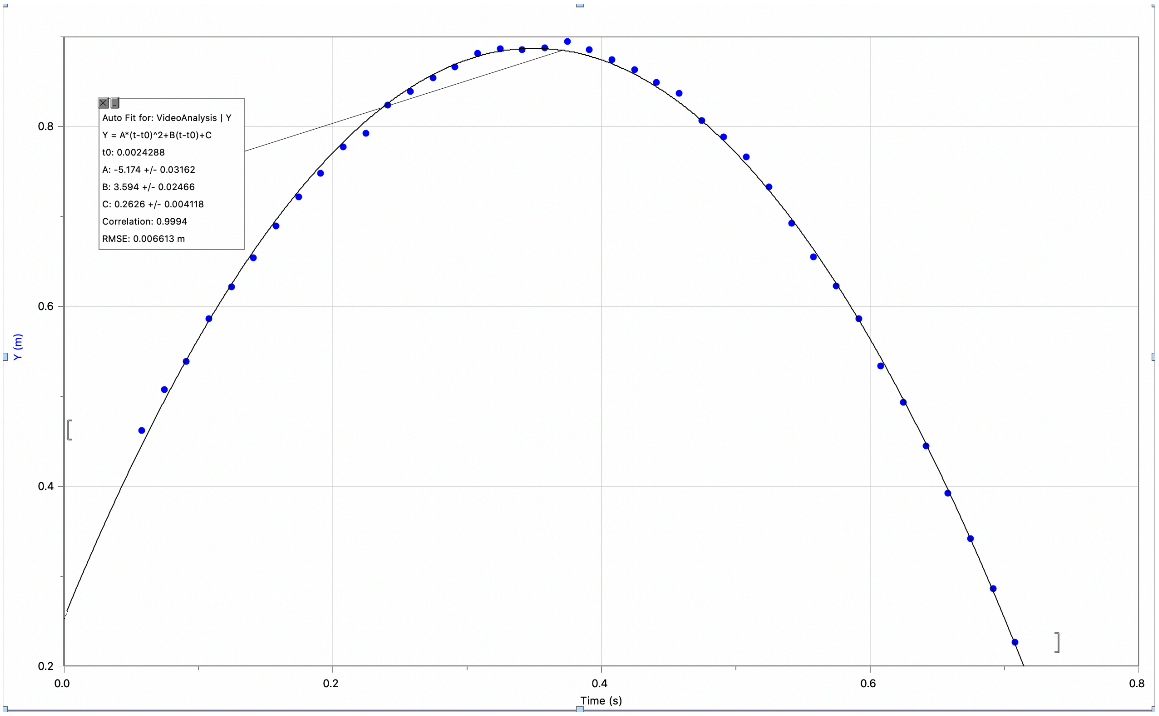
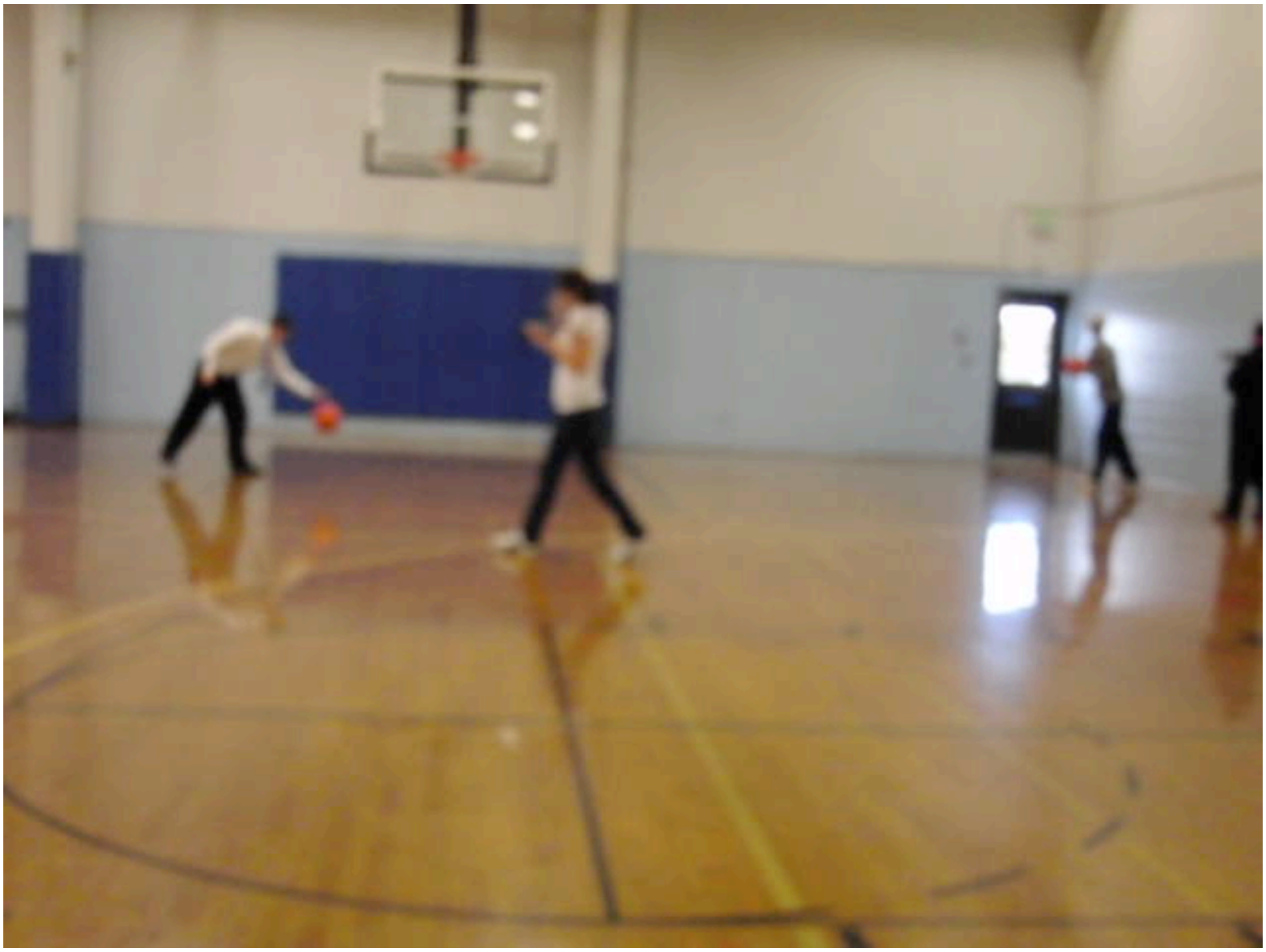



FIGURE 2.4: Curve Fit to Vertical Ball digitization

This fit gives a value for the acceleration of 2 x (5.174) = ~10.3 m/s$^2$, (remember again that we have to double the "A" parameter in the fit to get the acceleration) pretty close to the accepted value of *g* (~10 m/s$^2$).

## 2.2: Two Dimensional Motion

Now we are ready to look more closely at (i.e. analyze) a real two-dimensional trajectory. Instead of analyzing the shot put we are substituting a thrown basketball as shown in the video below (VIDEO 2.5.)



VIDEO 2.5: Basketball throw

https://digitalcommons.uri.edu/physicsofsports/14/

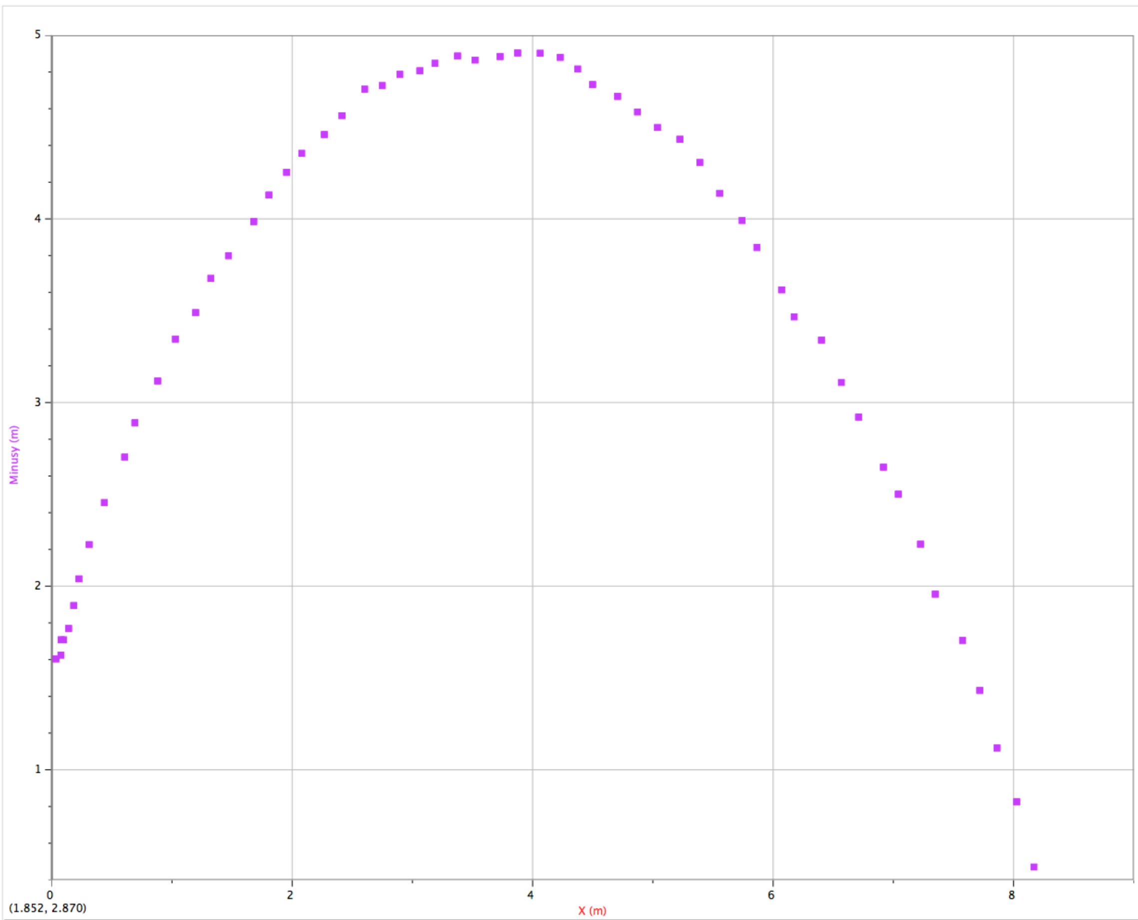



FIGURE 2.5: Basketball digitization

Note that the starting and ending heights are different. (Why is that?)

Below I display the position vs. time for the ball in the horizontal (x) and vertical (y) directions from my analysis of the video.

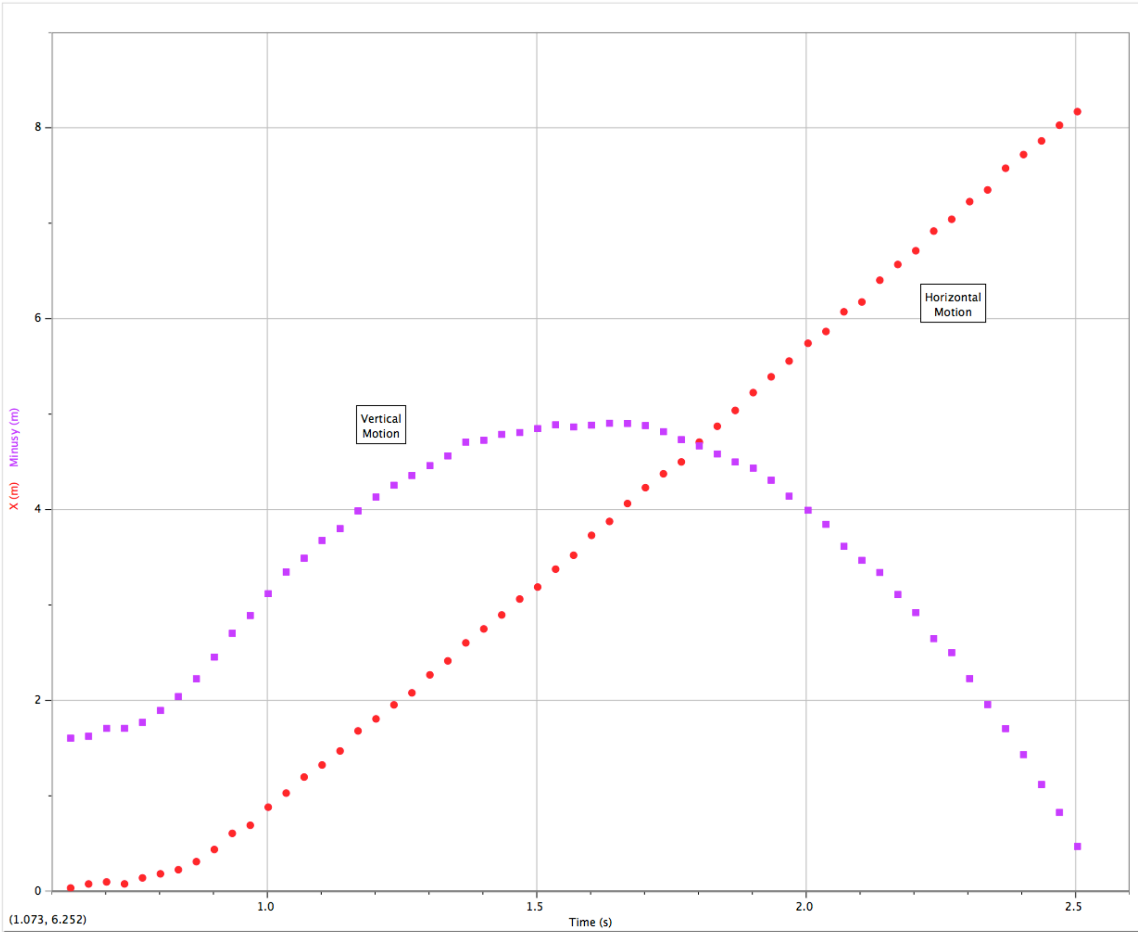



FIGURE 2.6: Distance vs. time plots of basketball

Hopefully you can see the similarities between the horizontal motion of the basketball in this curve with that of the horizontal motion of the rolling ball from the last section.

QUIZ 2.4

What statement best describes the <u>horizontal</u> motion of the basketball?

( ) The velocity is constant but the acceleration is changing.
( ) The acceleration is constant but the velocity is changing.
( x ) Both velocity and acceleration are constant.
( ) Both velocity and acceleration are changing.

The horizontal distance steps are approximately the same which tells us that the velocity is constant in the horizontal direction. If the velocity is constant, the acceleration is also constant (and equal to 0).

Likewise, the vertical plots of the shot in Figures 2.4 and 2.6 show some similarities. What are they?

QUIZ 2.5

What statement best describes the <u>vertical</u> motion of the basketball?

( ) The velocity is constant but the acceleration is changing.
( x ) The acceleration is constant but the velocity is changing.
( ) Both velocity and acceleration are constant.
( ) Both velocity and acceleration are changing.

The acceleration (due to gravity) is constant so the velocity is changing.

Now let's have the computer generate fits to both the horizontal and vertical data to check our assertions about the acceleration in the two directions.

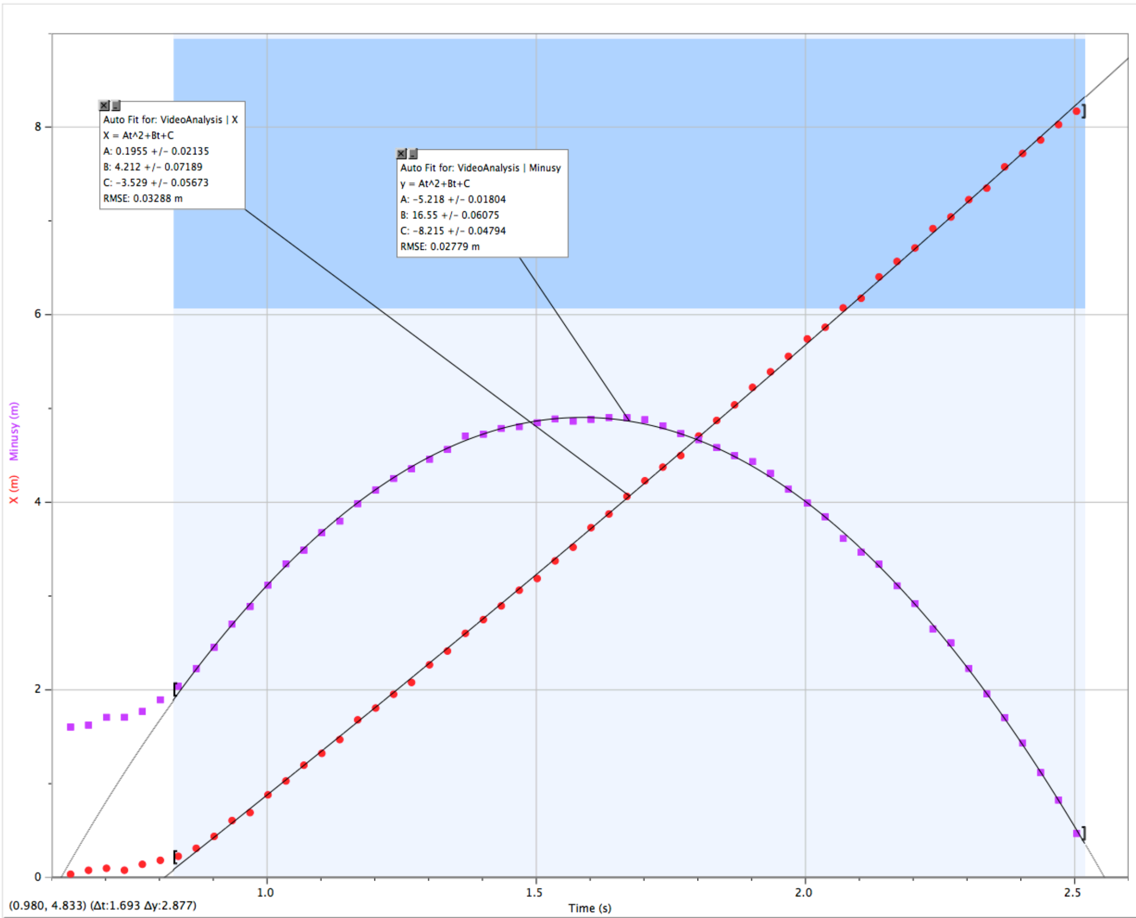



FIGURE 2.7: Curve fit to digitization of basketball throw

As expected, the horizontal acceleration is approximately 0 and the vertical acceleration is approximately equal to g, 10 m/s$^2$, exactly like the earlier analysis when a ball was rolled along the floor or shot straight up into the air. This ability to separate the analysis of horizontal and vertical motion is a real strength of the physics principles of kinematics.

To summarize, when quantitative analysis is called for, just as for one-dimensional motion, the average speed (horizontal or vertical) is still equal to the (horizontal or vertical) distance divided by the time and the average acceleration (horizontal or vertical) is still equal to the (horizontal or vertical) velocity divided by the time. For instantaneous velocity or instantaneous acceleration, we need to find the slopes of the appropriate curves or let the computer handle the analysis.

# 2.3: Two Dimensional Motion 2

In many sports activities, as in the shot put, the goal of the activity is to maximize the horizontal distance of a projectile (usually referred to as the "Range").

QUIZ 2.6

In what other sports is the goal to maximize the range of a projectile (that projectile could be the athlete performing the activity)? (Choose all that apply.)

( x ) The hammer throw
( ) 100 meter dash in running
( ) Tennis serve
( ) Slap shot in hockey
( x ) Kickoff in football
( ) Pole vault
( ) High jump
( x ) Long jump
( x ) Home run in baseball

However, in other sports activities, the goal of the activity is to maximize the height of a projectile (usually referred to as the "Height").

QUIZ 2.7

In what sports is the goal to maximize the height of a projectile (that projectile could be the athlete performing the activity)? (Choose all that apply.)

( ) The hammer throw
( ) 100 meter dash in running
( ) Tennis serve
( ) Slap shot in hockey
( ) Kickoff in football
( x ) Pole vault
( x ) High jump
( ) Long jump
( ) Home run in baseball

Can physics provide some information about the best approaches to maximize the range or height in given situations? Yes, is the answer.

Let's think about launching any of the projectiles that we have discussed. The two parameters that are most under the control of the athlete are the initial speed of the projectile and the angle (with respect to the horizontal direction) with which the projectile is launched. All other things being equal, a greater initial speed will result in a greater range and/or height. Just think about throwing a shot straight up. Wouldn't you expect the shot to travel to a greater height if you threw it up with a greater initial speed? It would be quite odd if that were not the case. Likewise, if you pushed the shot along the ice or rolled it along a floor with a greater initial speed, wouldn't you expect it to travel further? Both simple ideas apply to two-dimensional projectiles as well. The exact dependence on initial speed (using so-called "kinematic equations") we'll leave to a slightly more advanced physics book/course.

What about the importance of the initial launch angle? Under ideal conditions it is straightforward (in a slightly more advanced physics course) to analyze the trajectories of a projectile launched with different angles. It just takes the manipulation of a couple of kinematic equations. We plot below calculations of the trajectories of a projectile with the same initial speed for a few angles. To produce these plots it was assumed that the projectile (athlete, ball, hammer, or whatever) starts and ends at the same height.

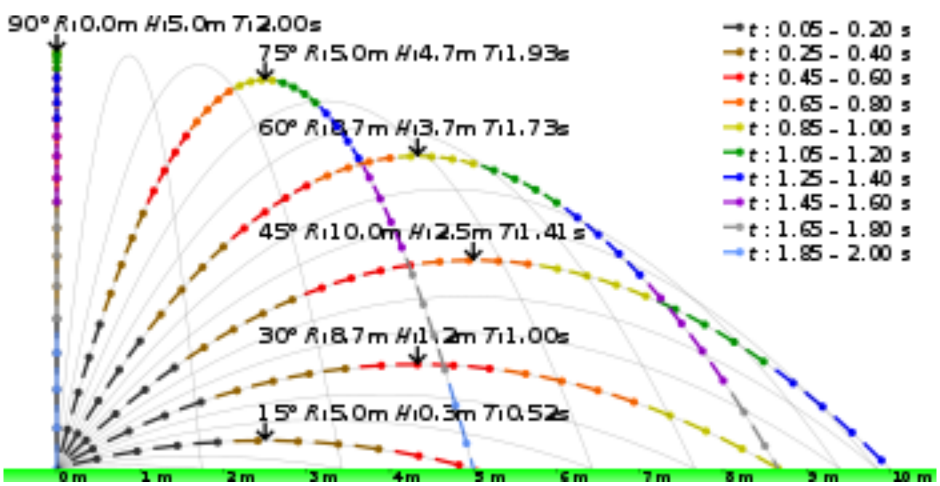



FIGURE 2.8: Trajectories of projectile vs. launch angle

http://upload.wikimedia.org/wikipedia/commons/thumb/6/61/Ideal_projectile_motion_for_different_angles.svg/350px-Ideal_projectile_motion_for_different_angles.svg.png

QUIZ 2.8

Based on the results plotted in Figure 2.8, for what initial angle is the range the greatest?

( ) 30°

( x ) 45°
( ) 60°

## QUIZ 2.9

Based on the results plotted in Figure 2.8, for which of these initial angles is the height the greatest?

( ) 30°
( ) 45°
( x ) 60°

From Figure 2.8, the greatest height is actually achieved for a 90° trajectory but the range in that case would of course be 0.

The plot in Figure 2.8 was generated assuming that the beginning and ending heights of the projectile were the same (for example from ground level to ground level). Obviously for the shot put that is not the case. As seen in the shot put or basketball video and in the analysis (Figure 2.7), while the shot ends up on the ground, the shot leaves Hoffa's hand at above head height. What effect do you think this would have on the optimum angle?

## QUIZ 2.10

To maximize the range of the shot put for different starting and ending heights, how should the optimum launch angle be adjusted (starting higher and ending lower)?

( x ) The launch angle should be less than 45°
( ) The launch angle should be greater than 45°
( ) The launch angle should still be equal to 45°

Under these more realistic conditions, the launch angle should be slightly less than 45°, approximately 40° - 42°. Can you see this? Imagine raising up all the curves in Figure 2.10 slightly. To still hit the same final position as the original "put", we would need to (slightly) decrease the angle from 45°.

Other factors we have neglected in the discussion above are the effects of air resistance, lift, and the spin of a projectile. Which of those do you expect will be important in the trajectory of Reese Hoffa's shot or in the flight of David Ortiz's home run? We'll learn more in later chapters.

We'll finish this chapter with a lesser-known sport in which the goal is to *maximize* the height of the projectile which involves *minimizing* the range. Can you guess which sport this is? I'm referring to the anvil launch or anvil shooting or firing, which has actually been around for more than 100 years.  Select VIDEO 2.6 to see a demonstration by world champion anvil shooter, Gay Wilkinson. Wow!

VIDEO 2.6:  Gay Wilkinson launches an anvil

https://digitalcommons.uri.edu/physicsofsports/15/

## Chapter 2 Homework

Questions

1. a. Ignoring air resistance, at what angle should a football be kicked for the range to be a maximum?

_____________ $^{o}$

b. At that same angle, how would the range be affected, if at all, if air resistance is taken into account?

(A) The range would increase.
(B) The range would decrease.
(C) The range would stay the same.

Answers: $45^0$, (B)

2. Ignoring air resistance, which of these angles for a kicked soccer ball gives the greatest range?

(A) $15^o$
(B) $30^o$
(C) $75^o$

Answer: (B)

3. a. Ignoring air resistance, which of these angles for a kicked soccer ball gives the greatest height?

(A) $15^o$
(B) $30^o$
(C) $45^o$
(D) $60^o$
(E) $75^o$

b. At that same angle, how would the height be affected, if at all, if air resistance is taken into account?

(A) The height would increase.

(B) The height would decrease
(C) The height would stay the same.

Answers: (E), (B)

4. Ignoring air resistance, what angle for a kicked soccer ball gives the same range as a ball kicked at 30$^o$?

(A) 15$^o$
(B) 45$^o$
(C) 60$^o$
(D) 75$^o$

Answer: (C)

5. A football is punted at two different angles, 60$^0$ and 75$^0$. Compare the results of the punts:

(A) The football punted at 60$^0$ has the greater range and the greater height.
(B) The football punted at 60$^0$ has the greater range but the lesser height.
(C) The football punted at 60$^0$ has the lesser range but the greater height.
(D) The football punted at 60$^0$ has the lesser range and the lesser height.

Answer: (B)

6. A speed skater rounds a turn on an oval speed skating track at constant speed. What can we say about her velocity and acceleration?

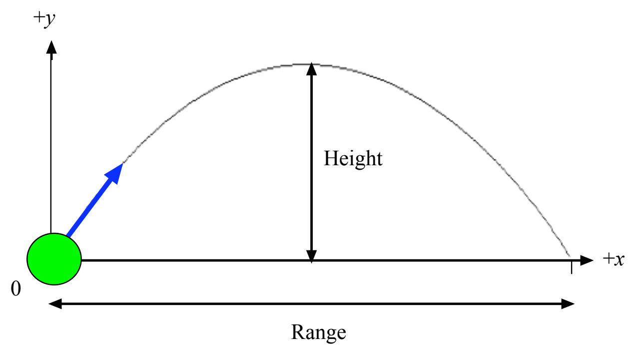
(A) Her velocity is constant; the acceleration is 0.
(B) Her velocity is constant; there is acceleration.
(C) Her velocity is not constant; the acceleration is 0.
(D) Her velocity is not constant; there is acceleration.

Answer: (D)

7. For which sport will air resistance play a greater role?

(A) Baseball
(B) Shot put

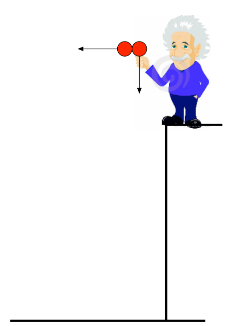
Answer: (A)




8. The range and height of a ball are calculated ignoring the effects of air resistance. If air resistance is taken into account, how will the range and height be affected?

(A) The range and height will stay the same.
(B) The range will stay the same but the height will decrease.
(C) The height will stay the same but the range will decrease.
(D) The range and height will both decrease.
(E) The range and height will both increase.

Answer: (D)

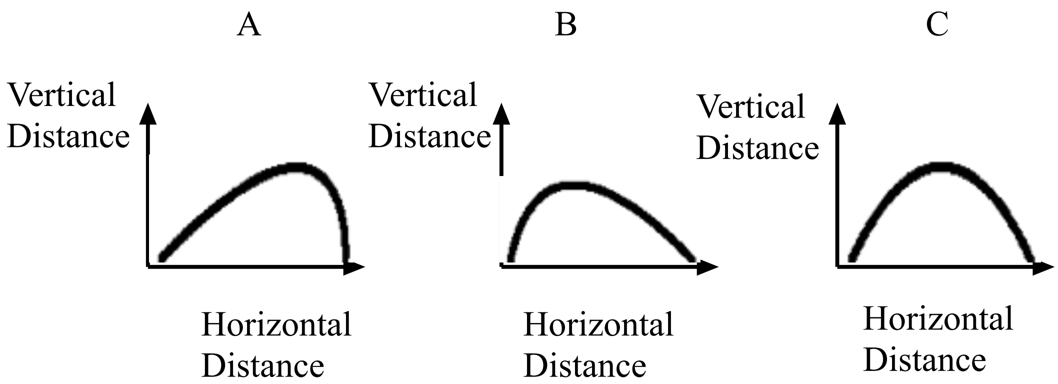


http://www.dreamstime.com/albert-einstein-thumb17041831.jpg

9. An athlete stands on the top of a cliff. He throws one ball horizontally away from the cliff while at the same time he drops a second ball straight down. Which ball will hit the ground first? (Assume no air resistance.)s

(A) The ball thrown out from the cliff.
(B) The ball dropped straight down.
(C) Both balls will hit the ground at the same time.
(D) The masses of the balls are needed to figure this out.

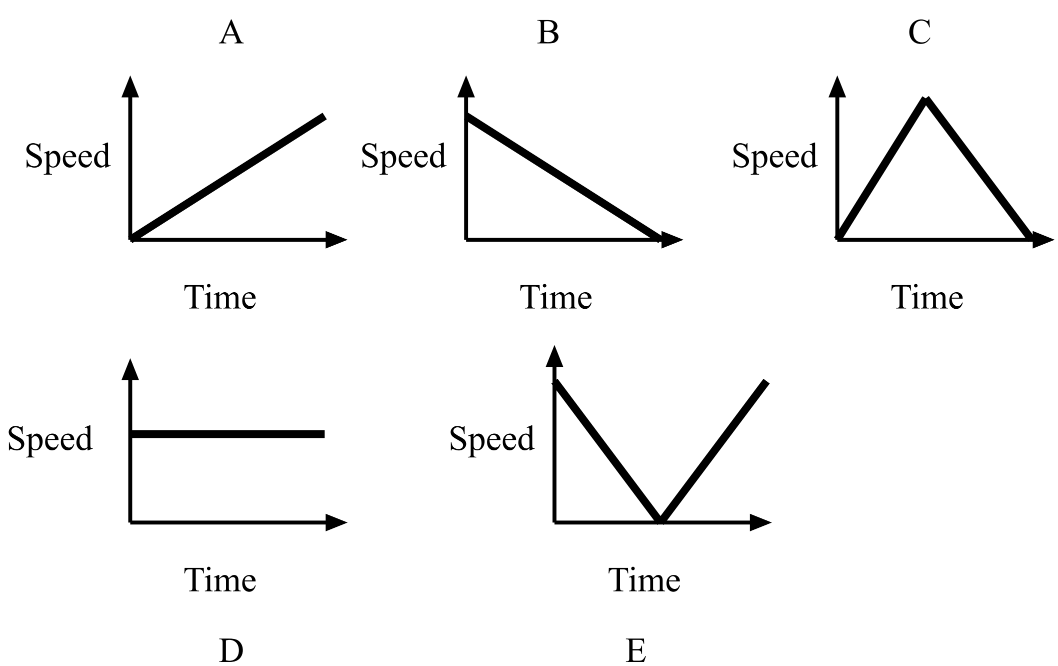
Answer: (C)




10. A shot is thrown into the air. Assuming we can neglect air resistance, which plot best depicts the trajectory of the shot?

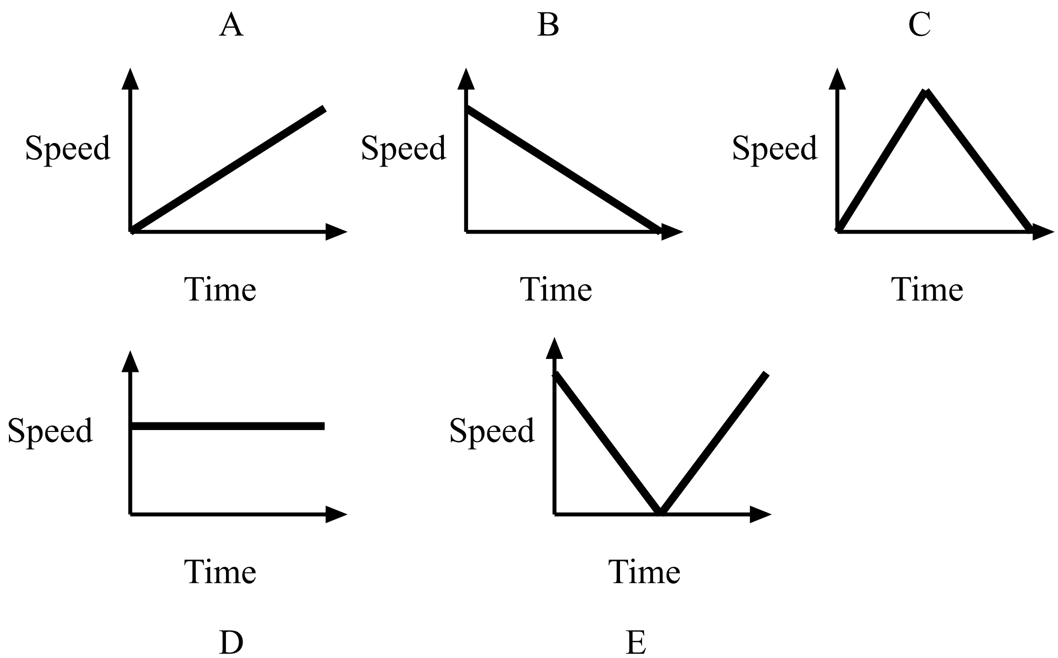
____________

Answer: (C)




11. A shot is thrown into the air. Which plot best depicts the speed of the shot in the vertical direction?

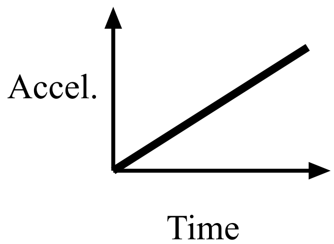
Answer: (E)



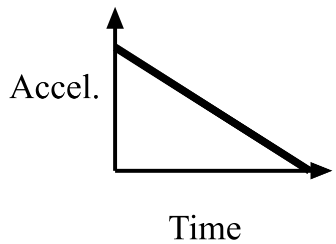

12. A shot is thrown into the air. Which plot best depicts the speed of the shot in the horizontal direction?

Answer: (D)

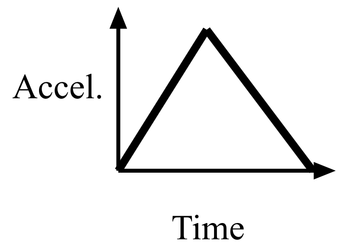
A

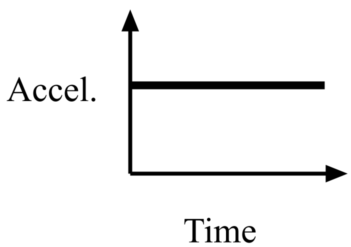



B

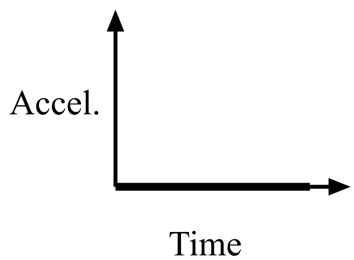



C




D




E

13. A shot is thrown into the air. Which plot best depicts the acceleration of the shot in the vertical direction?

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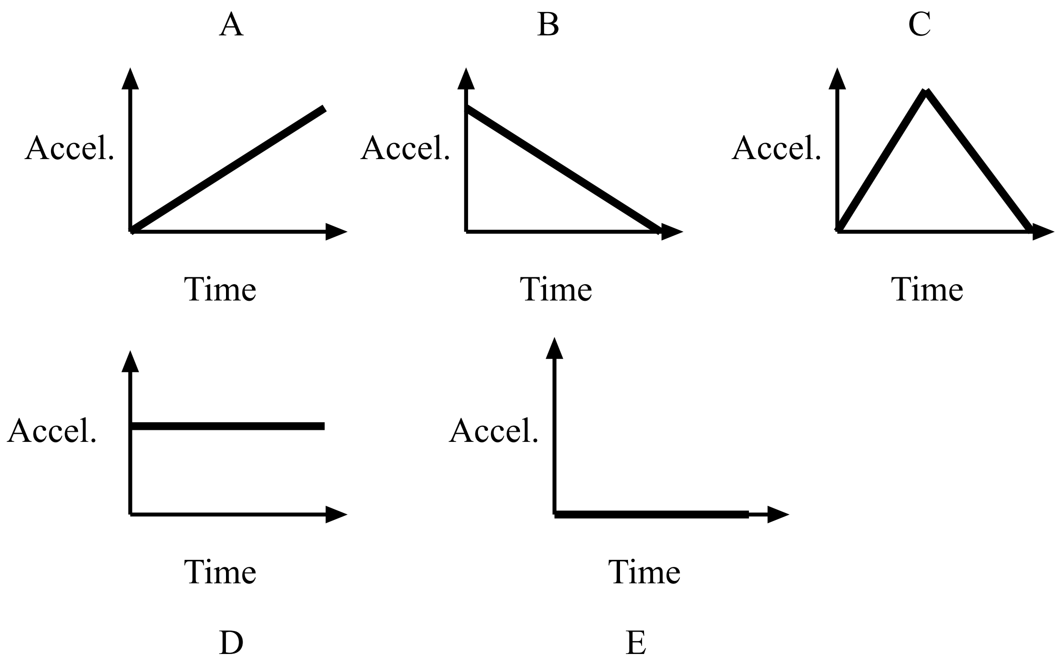
<u>Answer</u>: (D)



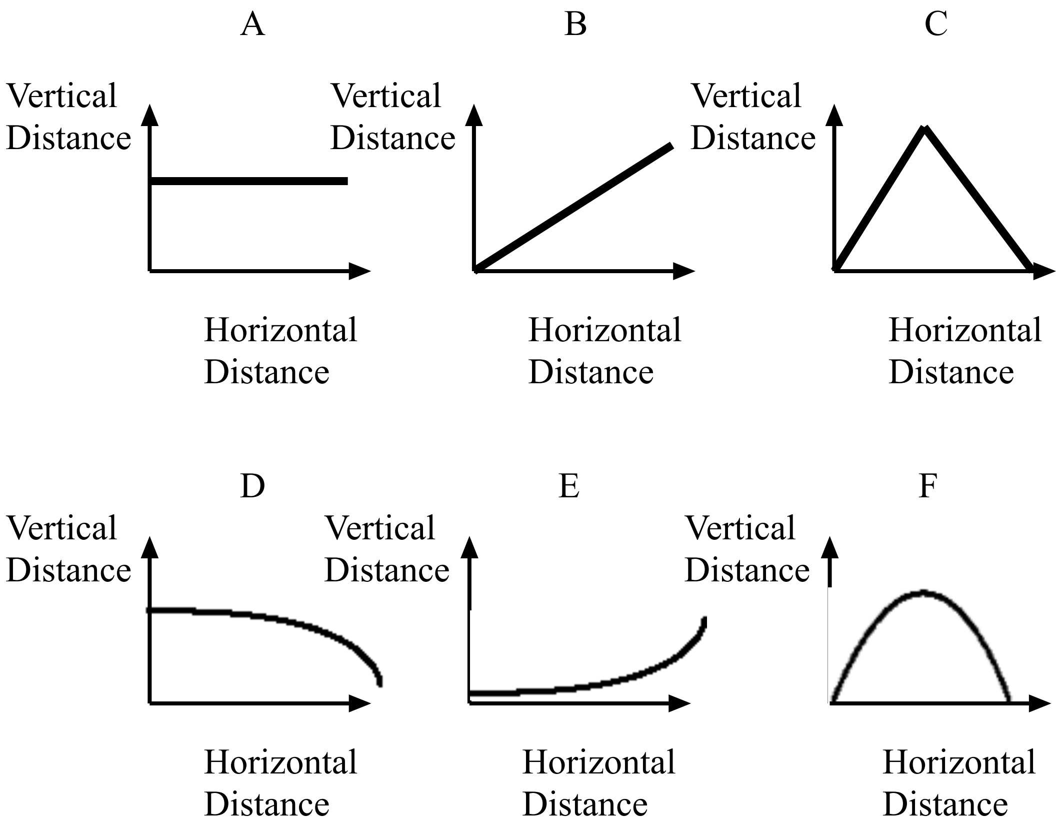

14. A shot is thrown into the air. Which plot best depicts the acceleration of the shot in the horizontal direction?

_____________

Answer: (E)

15. Rank the ranges of the projectiles in the events listed below:
- A discus
- B home run baseball
- C golf drive off the tee
- D shot put
- E long jump

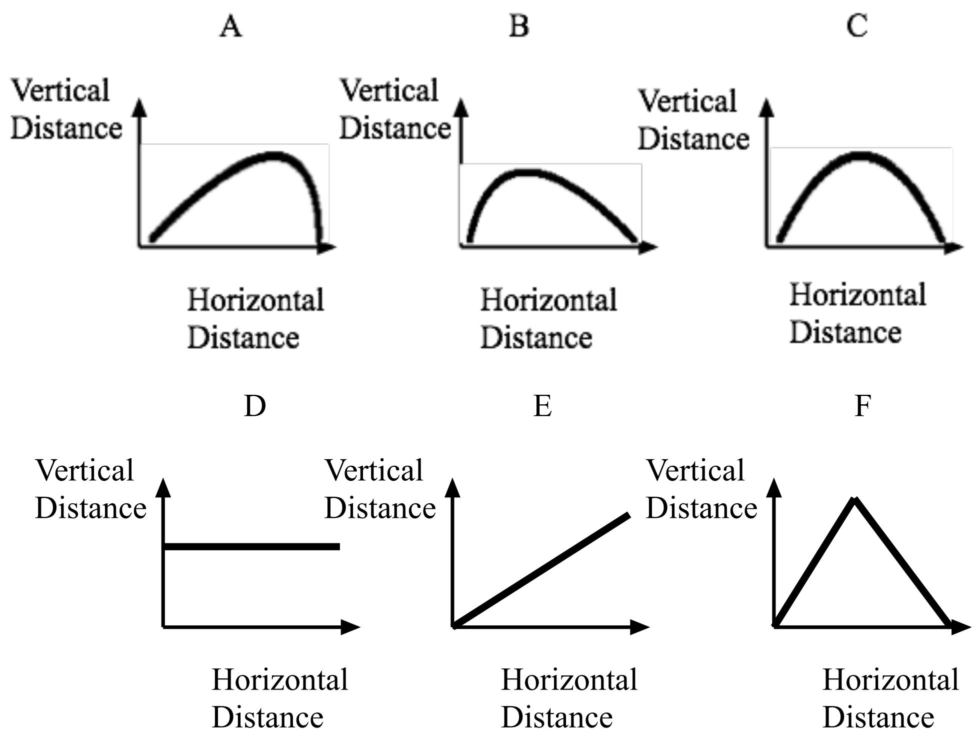
Answer: C > B > A > D > E




16. A shot is thrown out from a (motionless) satellite in deep space. We'll pick the "horizontal" direction as the direction perpendicular from the long axis of the satellite. Assume the shot is initially thrown out in this horizontal direction. Which plot best depicts the trajectory of the shot?

____________

Answer: (A)




17. A shot is thrown out from a (motionless) satellite in deep space. We'll pick the "horizontal" direction as the direction perpendicular from the long axis of the satellite. Assume the shot is thrown out at some angle with respect to the horizontal direction. Which plot best depicts the trajectory of the shot?

---

Answer: (E)

18. The maximum range of the shot put assuming that the ending height is the same as the starting height is obtained for a launch angle of ~45°. If the playing field slopes such that the ending height is below the starting height, what launch angle will give the maximum range?

(A) A launch angle of 45°.
(B) A launch angle greater than 45°.
(C) A launch angle less than 45°.

Answer: (C)

19. The maximum range of the shot put assuming that the ending height is the same as the starting height is obtained for a launch angle of ~45°. If the playing field slopes such that the ending height is above the starting height, what launch angle will give the maximum range?

(A) A launch angle of 45°.
(B) A launch angle greater than 45°.
(C) A launch angle less than 45°.

Answer: (B)

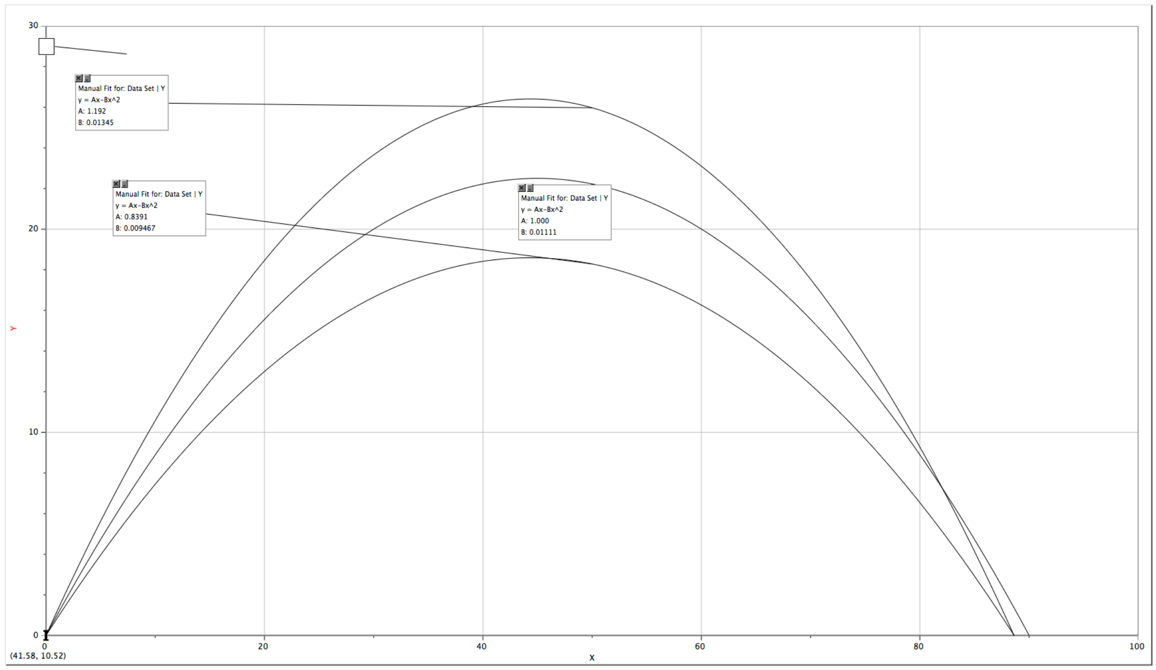
20. What factor or factors are more significant in affecting the trajectory of a baseball than a shot?

21. A shot is launched from a satellite in deep space. Describe its trajectory.

22. In the basketball video we analyzed, the starting and ending heights were different. Explain.

23. Can you give any sports examples in which maximizing the range of a projectile is not the goal? (anvil launch, diving, gymnastics, tennis)

24. Can you give any sports examples in which maximizing the height of a projectile is not the goal? (football field goal, home run in baseball, long jump)




25. A shot is thrown three times with the trajectories shown above. The initial speed is the same in each case, but the initial angle is varied with throws at 40$^o$, 45$^o$, and 50$^o$. Which is which? (Assume the same height at launch and landing and ignore the effects of air resistance.

40$^o$ ________

45$^o$ ________

50$^o$ ________

<u>Answers</u>:
40$^o$ A
45$^o$ B
50$^o$ C

## Exercises

1. A shot put is launched into the air and lands 75 feet from the launch point. Ignoring air resistance, what is the acceleration of the shot put in the vertical and horizontal directions during its flight (give your answers in $m/s^2$)?

vertical direction: __________ $m/s^2$

horizontal direction: __________ $m/s^2$

Answers: 0, 10 $m/s^2$

2. A shot put is launched into the air and lands 25 meters from the launch point. Ignoring air resistance, during its flight what is the acceleration of the shot put?

| | Horizontal Acceleration | Vertical Acceleration |
|---|---|---|
| (A) | 0 | 0 |
| (B) | 0 | 10 $m/s^2$ |
| (C) | 10 $m/s^2$ | 0 |
| (D) | 10 $m/s^2$ | 10 $m/s^2$ |

Answer: (B)

3. A plane is traveling 125 meters above the ground in a straight line at a constant speed of 100 meters per second. At one point a skydiver steps out of the plane. What is the horizontal speed of the skydiver just before she hits the ground? (Ignore air resistance.)

(A) 0
(B) 100 meters per second
(C) 150 meters per second
(D) 500 meters per second
(E) 600 meters per second

Answer: (B)

4. A plane is traveling 125 meters above the ground in a straight line at a constant speed of 100 meters per second. At one point a skydiver steps out of the plane. It takes 5

seconds to hit the ground. What is the vertical speed of the skydiver just before she hits the ground? (Ignore air resistance.)

(A) 0
(B) 50 meters per second
(C) 100 meters per second
(D) 150 meters per second
(E) 625 meters per second

Answer: (B)

5. A plane is traveling 125 meters above the ground in a straight line at a constant speed of 100 meters per second. At one point a skydiver steps out of the plane. It takes 5 seconds to hit the ground. What is the horizontal distance the skydiver has traveled before hitting the ground? (Ignore air resistance.)

_____________ meters

Answer: 500 meters

6. A plane is traveling 125 meters above the ground in a straight line at a constant speed of 100 meters per second. At one point a skydiver steps out of the plane. It takes 7 seconds to hit the ground.
a. Assuming the vertical speed of the skydiver when she hit the ground was 52.5 meters per second, what was the average acceleration of the skydiver in the vertical direction?

__________ $m/s^2$

Answer: 7.5 $m/s^2$

b. Explain this acceleration.

Answer: Gravity plus the affect of air resistance.

7. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. 2 seconds after the kick, what is the acceleration in the horizontal direction? (Ignore air resistance.)

(A) 0
(B) 10 $m/s^2$

(C) 20 $m/s^2$
(D) 50 $m/s^2$

<u>Answer</u>: (A)

8. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. 2 seconds after the kick, what is the acceleration in the vertical direction? (Ignore air resistance.)

(A) 0
(B) 10 $m/s^2$
(C) 20 $m/s^2$
(D) 50 $m/s^2$

<u>Answer</u>: (B)

9. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. 2 seconds after the kick, what is the horizontal component of speed? (Ignore air resistance.)

(A) 0
(B) 10 meters per second
(C) 20 meters per second
(D) 50 meters per second
(E) 70 meters per second

<u>Answer</u>: (C)

10. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. 2 seconds after the kick, what is the vertical component of speed? (Ignore air resistance.)

(A) 0
(B) 10 meters per second
(C) 20 meters per second
(D) 30 meters per second
(E) 50 meters per second
(F) 70 meters per second

<u>Answer</u>: (D)

11. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. How long does it take for the ball to reach its highest point? (Ignore air resistance.)

(A) 2 seconds
(B) 5 seconds
(C) 7 seconds
(D) 10 seconds
(E) 15 seconds
(F) 20 seconds

Answer: (B)

12. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. At its highest point, what is the acceleration in the horizontal direction? (Ignore air resistance.)

(A) 0
(B) 10 $m/s^2$
(C) 20 $m/s^2$
(D) 50 $m/s^2$

Answer: (A)

13. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. At its highest point, what is the acceleration in the vertical direction? (Ignore air resistance.)

(A) 0
(B) 10 $m/s^2$
(C) 20 $m/s^2$
(D) 50 $m/s^2$

Answer: (B)

14. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. At its highest point, what is the vertical component of speed? (Ignore air resistance.)

(A) 0
(B) 10 meters per second
(C) 20 meters per second
(D) 50 meters per second
(E) 70 meters per second

Answer: (A)

15. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. At its highest point, what is the horizontal component of speed? (Ignore air resistance.)

(A) 0
(B) 10 meters per second
(C) 20 meters per second
(D) 50 meters per second
(E) 70 meters per second

Answer: (C)

16. A ball is kicked with an initial horizontal speed of 50 meters per second and an initial vertical speed of 20 meters per second. What is the approximate acceleration in the vertical direction just before it hits the ground? (Ignore air resistance.)

(A) 0
(B) 10 $m/s^2$
(C) 20 $m/s^2$
(D) 30 $m/s^2$

Answer: (B)

17. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. After ~10 seconds it will hit the ground. What is the horizontal component of speed just before it hits? (Ignore air resistance.)

(A) 0
(B) 20 meters per second
(C) 50 meters per second
(D) 70 meters per second

Answer: (B)

18. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. After ~10 seconds it will hit the ground. What is the vertical component of speed just before it hits? (Ignore air resistance.)

(A) 0
(B) 20 meters per second

(C) 50 meters per second
(D) 70 meters per second

Answer: (C)

19. A ball is kicked with an initial horizontal speed of 20 meters per second and an initial vertical speed of 50 meters per second. What is the range of the ball? (Ignore air resistance.)

______________ meters

Answer: 200 meters

20. A ball is kicked with an initial horizontal speed of 50 meters per second and an initial vertical speed of 20 meters per second. What is the range of the ball? (Ignore air resistance.)

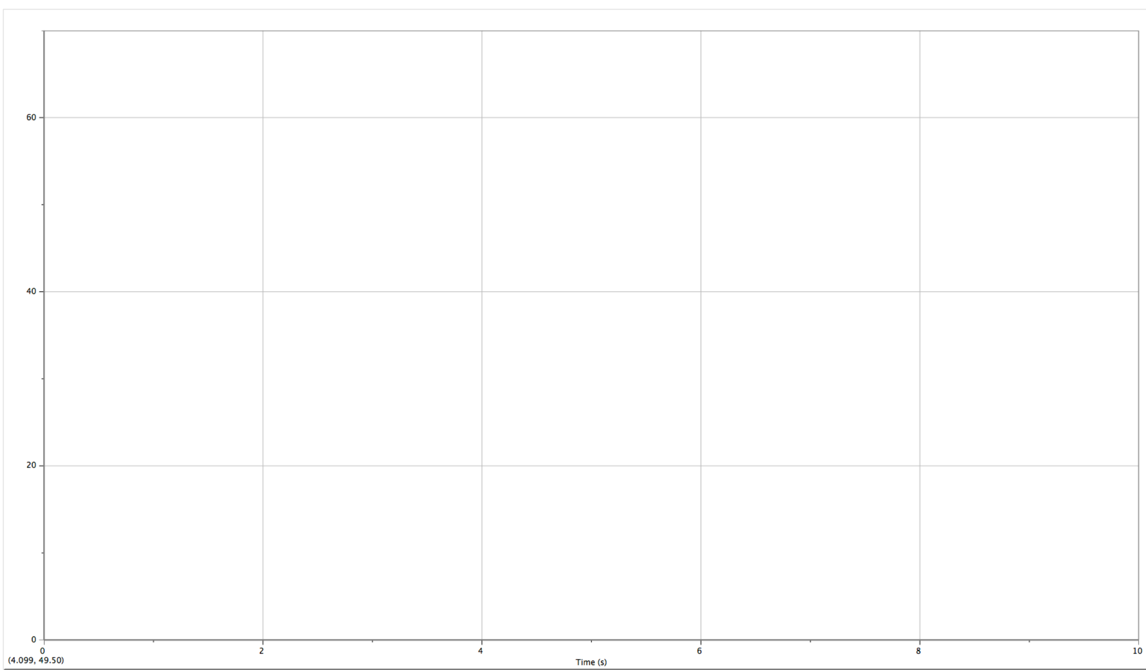
______________ meters

Answer: 200 meters

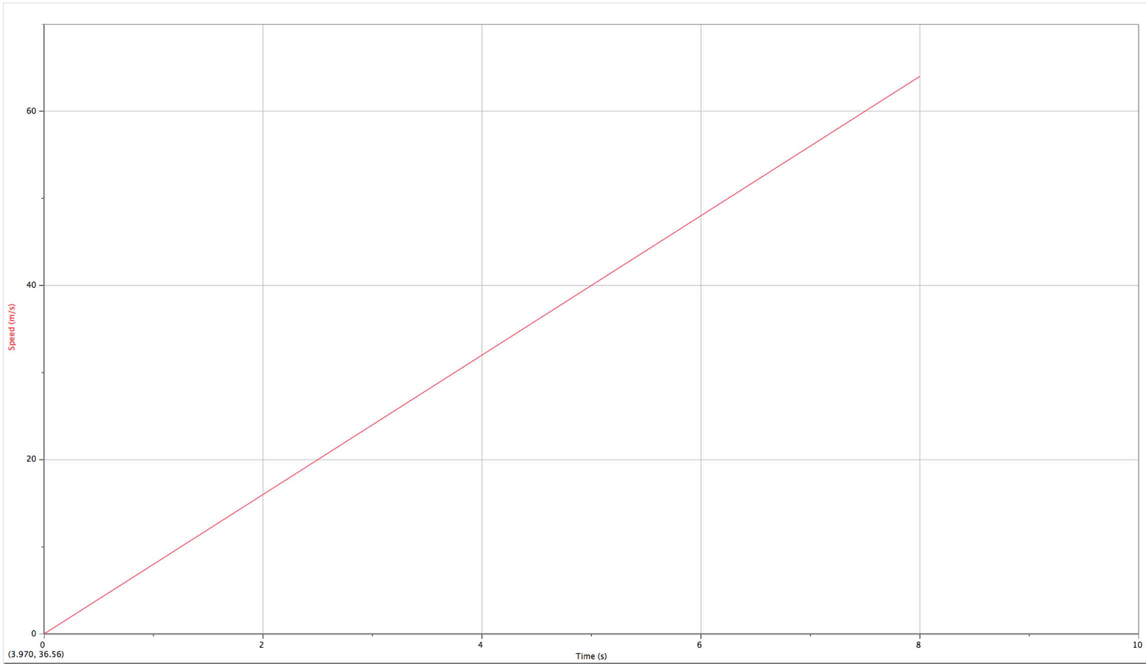
21. On Planet XXX, an astronaut throws a shot off a cliff in a horizontal direction. The data below depicts the speed vs. time of the shot in the vertical direction
a. Plot the data with speed on the vertical axis and time on the horizontal axis.
b. From the graph, find the average vertical acceleration of the shot (which is *g* on Planet XXX). Assume that air resistance is negligible.

| Speed (m/s) | Time (s) |
|---|---|
| 0 | 0 |
| 8 | 1 |
| 16 | 2 |
| 24 | 3 |
| 32 | 4 |
| 40 | 5 |
| 48 | 6 |
| 56 | 7 |
| 64 | 8 |

a.




Answer:




b.

___________ m/s$^2$

Answer: 8 m/s$^2$

22. On Planet XXX, an astronaut throws a shot off a cliff in a horizontal direction. The data below depicts the horizontal distance vs. time of the shot as it travels away from the cliff.

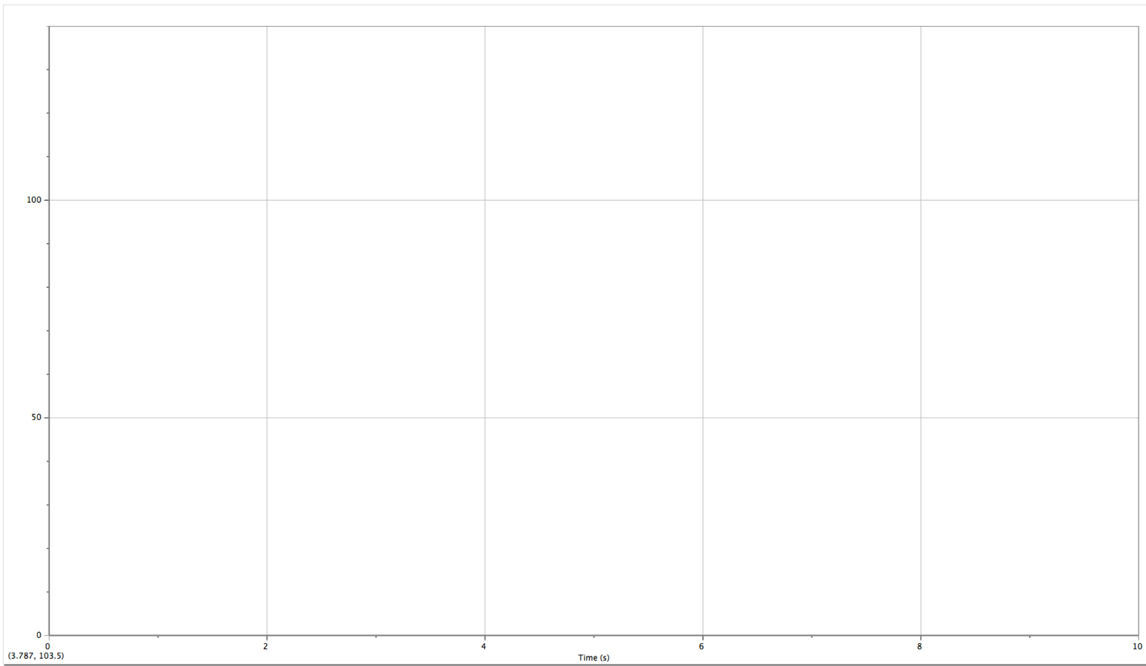
a. Plot the data with distance on the vertical axis and time on the horizontal axis.

b. From the graph, find the average horizontal speed and the average horizontal acceleration of the shot. Assume that air resistance is negligible

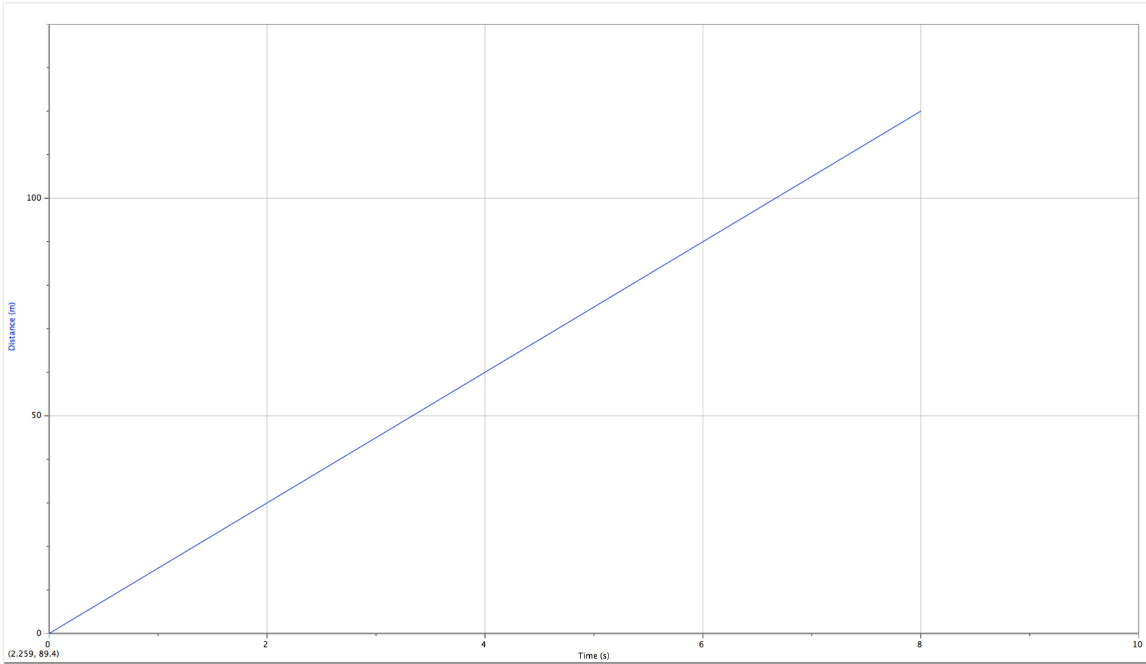
| Distance (m) | Time (s) |
|---|---|
| 0 | 0 |
| 15 | 1 |
| 30 | 2 |
| 45 | 3 |
| 60 | 4 |
| 75 | 5 |
| 90 | 6 |
| 105 | 7 |

120 8

a.




Answer:




b.

___________ m/s

___________ m/s$^2$

<u>Answers</u>: 15 m/s , 0

# CHAPTER 3: Newton's Laws


Marianne Vos of the Netherlands cycling in the 2008 Summer Olympics

http://autobus.cyclingnews.com/photos/2008/olympics08/25/4624_Marianne_Vos-st_gcPhSpt.jpg


VIDEO 3.1: Women's point race cycling final at the 2008 Summer Olympic games

https://digitalcommons.uri.edu/physicsofsports/16/

## 3.1: Newton's First Law

FIGURE 3.1: Start of a race

http://www.globalgiants.com/archives/fotos9/OlympRaceStart-01.jpg

The athletes in the image above are waiting for the "gun" to sound the start of their race. (Hopefully) before the gun sounds, they are not moving. (A gun may not actually be involved with the start of this race - see Chapter 9.) In physics we would say that they are "at rest" (though they would probably not describe their condition that way!).

QUIZ 3.1

After the gun sounds, how do the athletes transition from rest to running?

( ) The runners lean forward.
( x ) The runners push off from the starting blocks.

( ) The runners lift their hands off the ground.
( ) The runners raise up from their crouched positions.

The runners do all of the things listed above at the start of the race (why do they start in a crouched position anyway?) but the action that gets them moving forward is the push off the starting block. In physics, such a push is an example of a **force** and the start of the race is the essence of the first part of **Newton's First Law of Motion**, the first of three key laws that describe much of the physics of our everyday world. The first part of Newton's First Law states:

"An object at rest continues to remain at rest unless it is acted on by an external force."

Hopefully you can see the connection between this partial law and the start of the race depicted above (and basically just about any race). (We'll get back to the issue of which force is acting on which object a little later in this chapter.)

That takes care of objects at rest. What about objects that are in motion?

Let's consider the cycling video you watched at the opening of the chapter, which showed the Olympic gold medal-winning performance of Marianne Vos of the Netherlands (VIDEO 3.1). You may have noticed that the athletes alternated between cycling on a straight stretch of track and turning on a banked curve. (Why is the curve banked? We'll learn more about that later.) To go around the curves, the cyclists turned the front wheel of their bicycles in the direction of the turn.

QUIZ 3.2

What would have happened if the cyclists did not turn their wheels as they approached a curve?

( x ) The bicycles would keep traveling in a straight line (off the track!).
( ) The bicycles would turn in the direction of the curve anyway.
( ) The bicycles would turn away from the direction of the curve.
( ) The bicycles would stop suddenly.

I hope it is clear that the cyclists would keep traveling in a straight line if they did not turn their wheels. That takes care of the direction. What about the speed? Imagine if the cyclists stopped pedaling while they were riding on a straight section of track. What would happen? Of course, you would expect the bicycles to slow down and come to a stop eventually. But what makes a bicycle slow down?

## QUIZ 3.3

What causes a bicycle to slow down if the cyclist stops pedaling?

( ) Gravity
( ) The weight of the bicycle plus rider
( x ) A combination of various kinds of friction and air resistance

Hopefully you selected the third choice. Friction and air resistance are also types of forces just as is the push on the starting block at the start of the race. Now what if we could somehow eliminate all friction and air resistance (very desirable for the cyclist but <u>extremely</u> difficult to do in practice!). Then what happens?

## QUIZ 3.4

What would happen to the bicycle plus rider if the cyclist stopped pedaling while traveling along a straight path in an ideal (?) world without friction and air resistance?

( ) The bicycle would slow down anyway since the cyclist stopped pedaling.
( ) The bicycle would speed up once the cyclist stopped pedaling.
( x ) The bicycle would continue to travel at constant speed in a straight line.

It is the turning of the wheel that causes the bicycle to turn around the track and it is various forces that cause the bicycle to slow down. Eliminate these and we have the essence of the second half of Newton's First Law:

"An object in motion continues to travel in uniform motion (i.e. in a straight line at constant speed) unless it is acted on by an external force."

It took philosophers/scientists hundreds of years until Newton came along in the 17th-18th centuries to realize that the natural state of an object in motion is to <u>remain</u> in motion, <u>not</u> to come to rest. In retrospect it is very reasonable that this view was held for so long since it is almost impossible on Earth to completely eliminate "unwanted" forces such as friction and air resistance (unwanted sometimes anyway - when are friction and/or air resistance "desirable"?). One of the closest approximations to eliminating friction available today is an air track (shown below). Maybe you used one in a lab if you have taken a previous physics course.

FIGURE 3.2: Air Track

https://www.pasco.com/images/products/sf/SF9214_MAIN_170362.jpg

Interestingly, starting blocks similar to those depicted in Figure 3.1 are known as "Newton starting blocks" (not really blocks anymore). However, the origin of the name is not the scientist who discovered the laws of motion (Isaac Newton) but the inventor, Milton Newton, who was born in North Carolina in 1933.

## 3.2: Newton's Second Law

Let's now look more closely at the second part of Newton's First Law: An object in motion will continue to travel in a straight line at constant speed unless an external force acts on it.

QUIZ 3.5

In Chapter 1, we learned a specific term that describes straight line motion at constant speed. What is it?

( ) Constant distance
( ) Constant displacement
( x ) Constant velocity
( ) Constant acceleration

According to Newton's First Law, the natural state of motion therefore is one of constant velocity and it takes a force to change this.

QUIZ 3.6

Again from Chapter 1, what do we call a change in velocity?

( ) distance
( ) displacement
( ) speed
( x ) acceleration

According to Newton's First Law, the natural state of motion is constant velocity and it takes a force to change this. So apparently there is a connection between force and acceleration. What is it?

Let's take another look at the curling video we watched in Chapter 1, paying particular attention to the beginning. Select and watch VIDEO 3.2.


VIDEO 3.2: Curling competition from the 2010 Winter Olympics

https://digitalcommons.uri.edu/physicsofsports/17/

At the beginning of a "throw", the "thrower" pushes the "stone" along the ice. The thrower is applying a force which causes the stone to accelerate to a certain speed until it is released towards the "house". (By the way, to get started moving forward on the ice, the thrower pushes off from a "hack" which is quite similar to the starting blocks used in running races.)

QUIZ 3.7

Can you think of any other sports in which a force is applied to a sports object (which could be the athlete) to cause it to accelerate? Choose all that apply:

( x ) baseball
( x ) football
( x ) soccer

( x ) hockey
( x ) javelin throw
( x ) tennis
( x ) long jump
( x ) swimming
( x ) skiing
( x ) cricket

I would say that it is hard to think of any sport that does not involve some kind of force and acceleration. Can you come up with any examples?

Back to curling. A certain force is applied by the thrower to get the stone to accelerate. What if a different, more massive stone were used?

QUIZ 3.8

If a more massive stone were used in the curling throw, with the same force applied how do you think the acceleration would be affected?

( x ) The acceleration of the stone would be smaller.
( ) The acceleration of the stone would be greater.
( ) The acceleration of the stone would remain the same.

Newton realized with his Second Law that force and acceleration are linked by the mass of the object under consideration. So for a greater mass, the acceleration is reduced for the same force, or alternatively more force is needed to obtain the same acceleration. Hopefully, it also makes sense that if the mass is unchanged, more force will result in greater acceleration. That's the essence of **Newton's Second Law**. It could hardly be simpler since he found that these quantities are linearly related: Force equals mass times acceleration:

$$F = ma \qquad \text{Equation 3.1}$$

A few comments: First, since acceleration is a vector (it has both magnitude and direction) force must be a vector also (mass is just a number, called a "scalar" in the language of physics). So force can be negative or positive and can be broken into horizontal and vertical components if necessary; and this is important in many applications.

Second, let's talk about the units. We've mentioned previously that the SI unit of mass is the kilogram (kg) and we also worked out that the SI unit of acceleration is the meter per second squared ($m/s^2$). The combination unit for force ($kg \cdot m/s^2$) has been given a shorthand name of "Newton" (N) (named after Isaac Newton, not Milton Newton, in case you were wondering).

Third, in many cases several forces may be acting on an object. It is the sum (vector sum actually) of the forces, called the **net force**, that should be used in Equation 3.1.

Let's consider a couple of examples using this equation:

QUIZ 3.9

A force of 40 Newtons is applied to a curling stone resulting in an acceleration of 2 $m/s^2$. If a curling stone with twice the mass is used instead, what force must be applied to produce the same acceleration?

( ) 10 Newtons
( ) 20 Newtons
( ) 40 Newtons
( ) 60 Newtons
( x ) 80 Newtons
( ) 160 Newtons

QUIZ 3.10

A curling stone with a mass of 20 kilograms is accelerated to 1.5 $m/s^2$. What is the applied force?

_______________ Newtons

(Answer: 30 Newtons)

## 3.3: Newton's Third Law

Let's take another look at the runners positioned just before the start of a race, as shown below:

sed

FIGURE 3.3: Start of a race

http://www.globalgiants.com/archives/fotos9/OlympRaceStart-01.jpg

At this moment, they are "at rest" in a physics sense. A moment later they will all be moving forward. This obviously involves a change in velocity so clearly some acceleration is going on, which we now know means that a force is involved. What force? We already discussed the fact that the runners push off the starting blocks to get started, but that is a force that the runners are applying *to* the starting blocks. This cannot be the force that causes the runners to accelerate forward.

Newton also figured out this apparent dilemma with **Newton's Third Law**:

"Forces come in pairs, equal in magnitude but opposite in direction."

So the runners do push off from the starting blocks to "get going" (which we now know means to accelerate) but it is the equal (in magnitude) force from the starting blocks pushing on the runners that causes their acceleration. You can never have an isolated, single force in any situation. You can certainly have a single force acting on some object such as a runner, but there will always be an equal force acting in the opposite direction as well (this is sometimes called the "reaction force").

Let's put Newton's Third Law into practice:

QUIZ 3.11

What force accelerates a swimmer through the water?

( ) gravity
( ) air resistance
( ) the force the swimmer exerts pushing back on the water
( x ) the reaction force the water exerts on the swimmer

Hopefully it was clear that the last choice was the correct one in keeping with Newton's Third Law.

To observe another example of Newton's Laws at work in a sports setting, we'll now watch a segment from the 2008 season AFC Championship game between the Baltimore Ravens and the Pittsburgh Steelers. Select and watch VIDEO 3.3.

VIDEO 3.3: Segment from the 2008 season AFC Championship Game

https://digitalcommons.uri.edu/physicsofsports/18/

This video clip showed a pretty brutal collision between Baltimore Raven, Willis McGahee (mass = 107 kilograms), and Pittsburgh Steeler, Ryan Clark (mass = 93 kilograms). What can we say about the forces involved based on what we have learned about Newton's Third Law?

QUIZ 3.12

Which football player experienced the greater force in the collision

( ) Willis McGahee (mass = 107 kilograms)
( ) Ryan Clark (mass = 93 kilograms)
( x ) They experienced the same force (in magnitude).

From Newton's Third Law the force of the collision must be the same for both players despite the fact that their masses are different. This is one reason why in a two-car collision, the passengers in the less massive car are at greater risk - the force of the collision is the same for both cars. (Since the force is the same but the masses of the cars are different, what else about the cars would be different? Hint: see Newton's 2nd Law.) We'll talk much more about collisions in a later chapter.

## Chapter 3 Homework

Questions

1. A tether ball is spinning around a pole at constant speed. If the string were cut, in which direction would the ball travel?

(A) Straight up
(B) Straight down
(C) Radially outward from the circle it was making
(D) Perpendicular to the radius of the circle it was traveling in

Answer: (D)

2. In the hammer throw, the hammer is swung around in a circle before it is released. After release, it travels in a direction perpendicular to the circle it was tracing out. This motion is an example of which of Newton's Laws?

(A) 1st Law
(B) 2nd Law
(C) 3rd Law

Answer: (A)

3. The shot putter pushes on the shot with as much force as possible before it is released. After the shot is released, how much force is pushing on the shot? (Ignore air resistance.)

(A) No force
(B) Some force but less force than while the shot was in contact with the shot putter
(C) More force than while the shot was in contact with the shot putter

Answer: (A)

(Note: other forces may be acting on the shot after it leaves the putters hand - and probably are- but not a pushing force any longer.)

4. A baseball player hits a home run by hitting the baseball with the bat with a considerable amount of force. With how much force does the ball hit the bat during the collision.

(A) Less force than the force of the bat hitting the ball
(B) More force than the force of the bat hitting the ball

(C) The same force as the force of the bat hitting the ball

Answer: (C)

5. A shot is pushed with a certain force which causes it to accelerate. If the force pushing the shot is tripled, what will happen to the acceleration of the shot?

(A) The new acceleration will be the same as the original acceleration.
(B) The new acceleration will be three times the original acceleration.
(C) The new acceleration will be one third the original acceleration.

Answer: (B)

6. A shot is pushed with a certain force which causes it to accelerate. If a new shot is substituted with half the mass of the original shot with the same pushing force, what will happen to the acceleration of the shot?

(A) The new acceleration will be the same as the original acceleration.
(B) The new acceleration will be two times the original acceleration.
(C) The new acceleration will be one half the original acceleration.

Answer: (B)

7. A shot is pushed with a certain force which causes it to accelerate. If a new shot is substituted with twice the mass of the original shot with twice the pushing force, what will happen to the acceleration of the shot?

(A) The new acceleration will be the same as the original acceleration.
(B) The new acceleration will be two times the original acceleration.
(C) The new acceleration will be one half the original acceleration.

Answer: (A)

8. A shot is pushed with a certain force which causes it to accelerate. If a new shot is substituted with one half the mass of the original shot with twice the pushing force, what will happen to the acceleration of the shot?

(A) The new acceleration will be the same as the original acceleration.
(B) The new acceleration will be two times the original acceleration.
(C) The new acceleration will be one half the original acceleration.

(D) The new acceleration will be four times the original acceleration.
(E) The new acceleration will be one fourth the original acceleration.

<u>Answer</u>: (D)

9. In equation 3.1, Newton's 2nd Law, it is the net (total) force that is important. If only one force acts on a soccer ball, will the ball accelerate?

(A) Yes, in all cases
(B) Not necessarily

<u>Answer</u>: (A)

10. In equation 3.1, Newton's 2nd Law, it is the net (total) force that is important. If two forces act on a soccer ball, will the ball accelerate?

(A) Yes, in all cases
(B) Not necessarily

<u>Answer</u>: (B)

11. A bug splatters against an automobile window while the car is traveling at 60 mph. Which object experiences the greater force (in magnitude)?

(A) The car
(B) The bug
(C) The car and bug experience the same force.

<u>Answer</u>: (C)

12. A football player pushes against a tacking sled with a force of 35 Newtons. The sled does not move. What is the force of the sled on the athlete?

(A) 35 Newtons
(B) More than 35 Newtons
(C) Less than 35 Newtons
(D) The sled does not apply any force to the player.

<u>Answer</u>: (A)

13. A 280 pound basketball player staggers out of bounds and crashes into a 140 pound photographer. Compare the forces experienced by the two people.

(A) The force on the photographer was twice as great as the force on the basketball player.

(B) The force on the photographer was greater than the force on the basketball player but not twice as great.
(C) The force on the basketball player was twice as great as the force on the basketball player.
(D) The force on the basketball player was greater than the force on the photographer but not twice as great.
(E) The force on the basketball player was the same as the force on the photographer.

Answer: (E)

14. Why do runners start in a crouched position before the "gun" sounds?

15. Give some examples in which friction is "desirable".

16. Give some examples in which air resistance is "desirable".

17. A speed skater rounds a turn at constant speed. Is there a force on the skater?

(A) Yes
(B) No
(C) Not enough information is provided.

Answer: (A)

18. A football player pushes against a tacking sled but the sled does not move. Is there a force on the sled?

(A) Yes
(B) No
(C) Not enough information is provided.

Answer: (A)

19. A football player pushes against a tacking sled but the sled does not move. How many forces are there on the sled?

(A) 0
(B) 1
(C) 2
(D) at least 2
(E) more than 2

Answer: (D)

## Exercises

1. A 140 kilogram linebacker pushes on a 70 kilogram running back, driving him back towards the line of scrimmage. If the linebacker is pushing on the running back with 30 Newtons, what is the force of the the running back on the linebacker?

____________ Newtons

Answer: 30 Newtons

2. A quarterback is tackled by 2 lineman and pushed from each side by forces of 55 Newtons and 70 Newtons. Find the net force on the quarterback in Newtons.

____________ Newtons

Answer: 15 Newtons

3. The acceleration given to a hockey puck by a force is 25 m/s$^2$.
a. If the force is doubled, what will be the acceleration?
b. In the first case, if the force is 5 Newtons, what is the mass of the puck?

a. ______________ m/s$^2$

b. ______________ kilogram

Answers: 50 m/s$^2$, 0.20 kilogram

4. A force of magnitude $F$ produces an acceleration $a$ on an object of mass $m$. A force of magnitude $3F$ is exerted on a second object and an acceleration of $8a$ results. What is the mass of the second object compared to the first object?

(A) $3m$
(B) $9m$
(C) $24m$
(D) $(3/8)m$
(E) $(8/3)m$

Answer: (D)

5. A 100 kilogram man on ice skates pushes a 50 kilogram boy also on skates with a force of magnitude 50 Newtons. What is the magnitude of the force exerted by the boy on the man?

(A) 200 Newtons
(B) 100 Newtons
(C) 50 Newtons
(D) 40 Newtons
(E) 0 unless the boy pushes back.

<u>Answer</u>: (C)

6. In a World's Strongest Man competition, a contender pulls on a pallet loaded with concrete blocks. If he pulls on the pallet with 2000 Newtons, the pallet slides along the ground with an acceleration of 0.5 $m/s^2$. (Ignore friction - not a good assumption.) Find the mass of the pallet.

_____________ kilograms

<u>Answer</u>: 400 kilograms

7. In a World's Strongest Man competition, a contender pulls on a pallet loaded with concrete blocks. If he pulls on the pallet with 2000 Newtons, the pallet slides along the ground with an acceleration of 0.5 $m/s^2$. (Ignore friction - not a good assumption.) If the mass of the pallet is increased by 25%, how much force will the strong man need to keep the pallet moving with the same acceleration?

_____________ Newtons

<u>Answer</u>: 2500 Newtons

8. A curling stone has a mass of 20 kilograms. A curler applies a force of 30 Newtons to the stone. What is the acceleration of the stone?

______________ $m/s^2$

Answer: $1.5 \text{ m/s}^2$

9. A curler applies a force of 25 Newtons to a curling stone. The resulting acceleration of the stone is $1.47 \text{ m/s}^2$. What is the mass of the stone?

______________ kilograms

Answer: 17 kilograms

10. A curling stone has a mass of 20 kilograms. One curler applies a force of 30 Newtons to the stone. Another curler applies a force in the opposite direction. The acceleration of the stone is $1.0 \text{ m/s}^2$. How much force did curler #2 apply to the stone? (Hint: there are 2 possible answers.)

_____________ Newtons

or

_____________ Newtons

Answers: 10 Newtons or 50 Newtons

11. A curling stone of mass 17 kilograms is pushed from rest with a constant force for 5 seconds. At the end of 5 seconds, the speed of the stone is 10 meters per second. Find the force.

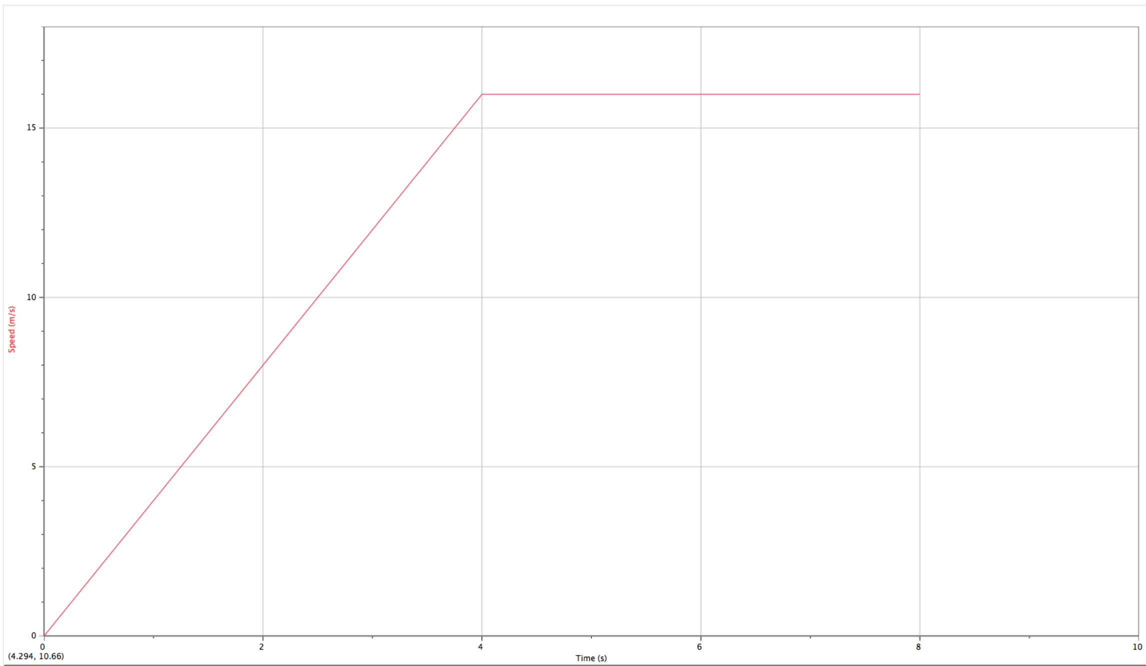
_____________ Newtons

Answer: 34 Newtons

12. A curling stone is pushed from rest with a constant force of 100 Newtons for 3 seconds. At the end of 3 seconds, the speed of the stone is 15 meters per second. Find the mass of the stone.

______________ kilograms

Answer: 20 kilograms




13. A curling stone of mass 20 kilograms is pushed from rest with a variable force for 8 seconds resulting in a change in speed with time as shown above. Find the force:
a. in the 0-4 second time period

______________ Newtons

b. in the 4-8 second time period

______________ Newtons

Answers: a. 80 Newtons
b. 0

14. A bowling ball (weight of 15 pounds) leaves the hand of the bowler with a speed of 20 mph. The bowler was pushing on the ball for 3 seconds before the release. Find:
a. the average acceleration of the ball

________________ $m/s^2$

b. the average force the bowler exerted on the ball.

_____________ Newtons

Answers: a. 2.98 $m/s^2$
b. 19.9 Newtons

15. A football player pushes against a tacking sled with a force of 50 Newtons but the sled does not move. What is the magnitude of the net force on the sled?

(A) 0
(B) 25 Newtons
(C) 50 Newtons
(D) 100 Newtons
(E) none of the above

Answer: (A)

# CHAPTER 4: Forces

Strongman Mariusz Pudzianowski of Poland holds up an Atlas Stone

https://live.staticflickr.com/7264/7472035744_95374a31d0_b.jpg


VIDEO 4.1: The Atlas Stone event of the
2010 World's Strongest Man competition from Sun City, South Africa

https://digitalcommons.uri.edu/physicsofsports/19/

Select and watch VIDEO 4.1.

In the previous chapter we encountered a few forces such as the push of the runner against the starting block at the beginning of a race (and the push of the starting block back against the runner) and the push off from the hack at the start of a curling throw. In this chapter we'll examine a few more forces that are important in physics (and in sports).

## 4.1: Mass and Weight

In the video opening this chapter you watched the signature and final event of the 2010 World's Strongest Man competition from Sun City, South Africa. In that event, Brian Shaw from the U.S. defeated Zydrunas Savickas from Lithuania, who, however was winner of the overall competition. The Atlas Stones used in the event are five stones of increasing **mass** and **weight**, and they are obviously quite massive and weighty. But what are mass and weight anyway? Are they the same? Are they both forces? ("No" and "no" to the last two questions.)

One way to think of mass is as a bookkeeping method for keeping track of the amount of material in an object. All objects are composed of various kinds of atoms. Atoms are composed of what?

QUIZ 4.1

Of what are atoms composed (choose all that apply):

( x ) protons
( x ) neutrons
( x ) electrons

As examples, (from the periodic table) a neutral carbon atom always has 6 protons, 6 electrons, and usually 6 neutrons. A neutral iron atom always has 26 protons, 26 electrons, and on average 30 neutrons. (If the atom is not "neutral"-an “ion”- that means it has a different number of electrons, but the number of protons is the same.) A value of mass is assigned to the proton; the mass of the neutron and electron are measured relative to this mass. The mass of the neutron is approximately equal to the mass of the proton; the mass of electron is approximately 1/2000th of the proton mass and is often ignored in mass calculations.

The mass of an individual proton or atom is very, very small, as you might imagine. But put enough of them to together and you have the kinds of masses we deal with in everyday objects, for which the SI unit is the kilogram (kg). The important thing to remember about mass is that the mass is not affected by outside influences such as external forces. A carbon atom always has 6 protons, etc. and the mass of each proton is always the same. That's a good thing since if the mass were affected by forces for example, then from Newton's equation, F = ma, the everyday world would be much more complicated (think about it!).

That's mass, basically. What about "weight". Weight is a force, the response of the mass of an object to gravity. There is a simple equation for calculating the weight, W, also known as the **gravitational force**, of an object under the relatively simple circumstances we are concerned with here:

$$W = mg \qquad \text{Equation 4.1}$$

We've already encountered "little $g$" before, the acceleration due to gravity, with a value near the surface of the Earth of approximately 10 $m/s^2$. Let's look at some numbers.

QUIZ 4.2

A two liter bottle of Coke (or of water) has a mass of approximately two kilograms. What is the approximate weight (remember that weight is a force so the SI unit is the Newton)?

( ) 5 Newtons
( ) 10 Newtons
( x ) 20 Newtons
( ) 30 Newtons
( ) 40 Newtons
( ) 60 Newtons

We just used equation 4.1 with the mass and $g$ as given above.

To make the connection with our everyday units, a force of 1 Newton is equivalent to a force of approximately 1/5 pound (lb) (more specifically, 1 Newton = 0.2248 pound).

QUIZ 4.3

What is the approximate weight of a two liter bottle of Coke in pounds?

( ) 1 pound
( ) 2 pounds
( ) 3 pounds
( x ) 4 pounds
( ) 5 pounds
( ) 8 pounds
( ) 10 pounds
( ) 20 pounds
( ) 100 pounds

Now if we consider the Atlas Stones event again, hopefully you can better appreciate the mass and weight involved. The 5 Atlas Stones used in the World's Strongest Man competition vary in mass from 100 kilograms to 160 kilograms. Let's talk about the 120 kilogram stone.

Or QUIZ 4.4

What is the approximate weight of the 120 kilogram Atlas stone in Newtons?

( ) 12 Newtons
( ) 120 Newtons
( ) 240 Newtons
( ) 600 Newtons
( x ) 1200 Newtons
( ) 2400 Newtons
( ) 6000 Newtons

That stone is 60 times greater than the weight of a 2 liter bottle of Coke (in pounds that would be ~265 pounds). I couldn't pick that up. Could you?

A final check for now on mass vs. weight. For a new twist of the Strong Man competition, we take our 120 kilogram Atlas Stone to the moon (much more on this topic in Chapter 10), where the force of gravity is approximately 1/6 that of Earth. What about the mass and weight there?

QUIZ 4.5

On the Moon, what is the approximate mass of the 120 kilogram Atlas stone?

( ) 10 kilograms
( ) 20 kilograms
( ) 40 kilograms
( ) 60 kilograms
( x ) 120 kilograms
( ) 200 kilograms
( ) 720 kilograms

I hope you selected correctly that the mass <u>does not change</u>.

QUIZ 4.6

On the Moon, what is the approximate weight of the 120 kilogram Atlas stone?

( ) 10 Newtons
( ) 20 Newtons
( ) 40 Newtons
( ) 60 Newtons
( ) 120 Newtons
( x ) 200 Newtons
( ) 720 Newtons

For this exercise you take the weight of the stone on Earth from Quiz 4.4 and divide by 6, the difference in the gravitational force between Earth and the Moon.

So would the "Moon's Strongest Man" competition by easier or harder than the one we already took a look at on Earth? And how would you change it, if at all? We'll discuss this in Chapter 10.

## 4.2:  Tension and Normal Force

To see some other forces at work, we'll watch another event from a World's Strongest Man competition. Select VIDEO 4.2 and watch as Mariusz Pudzianowski from Poland competes in the plane pulling event in the 2008 Finals held in Charleston, West Virginia. He ended up winning this event and became the overall winner of the competition, his fifth title as World's Strongest Man. Since a timer is conveniently included in the video, make a note of the final time so we can calculate the average speed before we get too rusty.


VIDEO 4.2:  Mariusz Pudzianowski from Poland competes in the plane-pulling event of the 2008 World's Strongest Man competition.

https://digitalcommons.uri.edu/physicsofsports/20/

QUIZ 4.7

I got a time of 36.67 seconds. How about you? Using this time and the distance the plane was pulled as 25 meters, calculate the average speed of the plane.

________________ meters per second

(Answer: (25 m)/(36.67 s) = 0.68 meters per second)

(This is not a very impressive speed compared to sports speeds we have encountered in earlier chapters! = why not?!)

At the beginning of the video, the plane is at rest, then it starts moving as the trial starts. Since the velocity of the plane changed, the plane accelerated so a force of some kind was involved. Mariusz pulls on the strap that is attached to the plane, so the force on the plane is provided by the strap. When a strap or rope or chain or other flexible material exerts a force we call that force the **tension**, usually labeled, T. At the end of the event, the strap (and Mariusz) are laying on the ground so the strap no longer exerts any force (the strap is no longer tight or "tense").

Now is the tension in the strap the only force involved in the motion of the plane along the runway? Specifically, are there any other forces on the plane that are acting in the same direction as the tension in the strap or in the opposite direction? (The answer is "Yes".) What are they?

QUIZ 4.8

What other forces act on the plane either in the direction of tension or opposite to that direction (i.e. parallel to the ground)? (Check all that apply.)

( ) Gravity
( ) The weight of the plane
( ) Mariusz's weight
( x ) Various kinds of friction

Gravity and the weight act in a direction *perpendicular* to the tension so they are not directly involved in the motion of the plane. Also, Mariusz's weight is a force but it is not a force on the plane anyway. We will talk more about friction in the next section but I'm sure you are aware that there is some kind of friction involved in opposing the forward progress of the plane. If there were no friction or other opposing forces, it would at least be "easier" to pull the plane, but definitely not "easy"!

Once Mariusz gets the plane moving, it appears to be moving at approximately constant speed (and constant velocity). (This is just my estimate - if we had a video taken with a stationary camera we could digitize the video and find out. If you can arrange such a plane-pulling exercise at your home or in your class, that would be great!)

QUIZ 4.9

If the velocity of the plane was constant for some period of time during the event we watched, what could we say about the acceleration during that time?

( x ) The acceleration was zero.
(   ) The acceleration was increasing.
(   ) The acceleration was decreasing.
(   ) The acceleration was constant but not zero.

Constant velocity means zero acceleration. Does this mean from Newton's Second Law (F = ma) that the force on the plane is also zero? No. This means that the tension in the strap is approximately equal to the opposing force(s) of friction. As mentioned in the previous chapter, Newton's Second Law should be more correctly stated that the total force (usually "net" force in physics lingo) is equal to mass times acceleration. It's common to have multiple forces acting on an object in different directions at the same time. If forces happen to cancel such that the object is moving with constant velocity, as appears to be the case with the plane in the video for at least a portion of the event, then in physics we say that the object is in **dynamic equilibrium**.

If forces cancel such that an object is not moving, we say the object is in **static equilibrium**. A good example of static equilibrium is depicted below, a shot from the "Pillars or Hercules" event in World's Strong man competition (what else!). What forces are at work in this event?


FIGURE 4.1: The Pillars of Hercules event from the World's Strongest Man competition

http://theworldsstrongestman.com/wp-content/uploads/2014/07/Pillars-of-Hercules.jpg

Let's consider the plane again before Mariusz starts pulling on the strap attached to it. Are there any forces acting on it at that time? Of course - gravity/the weight of the plane. Is that it?

QUIZ 4.10

Before the plane starts moving, is gravity the only force acting on it?

( ) Yes, there are no other forces involved.
( x ) No, there must be another force or forces since the plane is not accelerating.

What is that other force (or forces)? When an object is resting (or moving) on a flat surface, there will in almost all cases be a force from the surface pushing on the object. In physics this is known as the **Normal Force**, usually abbreviated as N. If as in the case of the plane, the normal force is just opposing and cancelling the weight of the plane (which is 88,000 pounds!), then the normal force must be equal to that weight. There are other cases we'll discuss later in which the normal force is not simply equal to the weight of the object.

Let's wrap up this section by considering a few scenarios in which objects may or may not be in some kind of equilibrium.

QUIZ 4.11

For the objects and situations listed below, decide if the object is in equilibrium or not and if in equilibrium, which kind.

| Object/situation | Static Equilibrium | Dynamic Equilibrium | Neither |
|---|---|---|---|
| a. Plane in video before it starts moving | x | | |
| b. Pillars in the "Pillars of Hercules" event as shown in Figure 4.1 | x | | |
| c. Pillars in the "Pillars of Hercules" event after the strong man releases the ropes | | | x |
| d. Cyclist making a turn on a track at constant speed | | | x |
| e. Runner traveling along a straight track at constant speed | | x | |
| f. Skier accelerating down a | | | x |

mountain

Did you choose correctly? In examples b., c., and e., there is acceleration due to a change in speed and/or a change in direction so the object in each case is <u>not</u> in equilibrium.

## 4.3: Friction

I'm sure you knew something about the force of **friction** before reading this book. We've just discussed it a little in the previous section and it also came up in Chapter 3 when we analyzed a cycling race. It's hard to get rid of friction even when you want to, and that was no doubt one reason it took so long for someone (Newton) to realize that the natural state of an object in motion was to remain in motion, not to come to rest, as we discussed in the last chapter.

There are several kinds of friction but they have quite a lot in common. First let's think about an object sliding along some surface. We've already considered the example of curling. If the object is in any sort of contact with the surface underneath (i.e. it's not riding on an air cushion like an air track or air hockey table) then there will be some rubbing of some kind going on that acts against the direction of motion. If there are no other forces involved, this slows the object down (acceleration) so it must be a force. For a moving object this force is known as sliding or **kinetic friction** and is abbreviated as $f_k$.

Now think back to the curling video (we've watched it twice - that's enough for now.) At the beginning of the throw the thrower travels along with the stone, pushing it along the ice. Therefore, two horizontal forces are acting on the stone: the pushing force, we'll call P, and friction in the opposite direction. A sketch of the stone and the horizontal forces involved would look like this (called a **free body diagram**):

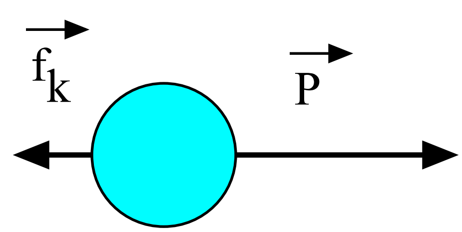



Figure 4.2: Top view of the throw of a curling stone.

A couple of remarks about this diagram. First, since the stone accelerates towards the target (at least at first), the pushing force must be greater than the frictional force. This is indicated by the fact that the arrow associated with the pushing force is greater in length than the frictional force arrow. (We should expect that the frictional force between the stone and the ice should be rather small; otherwise, why play the game on ice!?) Second, we have used the conventional notation for vectors by placing arrows over the symbols for the forces.

Even if the ice and the stone are both nice and smooth, there will be some kinetic friction force opposing the motion. Next question: what if we replace the stone with a more massive one?

QUIZ 4.12

If the curling stone is replaced by a more massive one, what will happen to the frictional force?

( ) The frictional force will decrease.
( x ) The frictional force will increase.
( ) The frictional force will remain the same.

The magnitude of the frictional force is related in my way of thinking to the degree to which the two surfaces in contact are "squashed" together (not a physics term!). More mass on the top object will result in greater pressing together of curling stone to ice, which increases the rubbing together of the surfaces and increases the frictional force. So the frictional force scales somehow with the mass (weight really), and in fact is <u>linearly proportional to the weight under simple conditions</u>. (For more complicated situations than an object sliding along a horizontal surface with no other forces to consider, the frictional force will be <u>proportional to the normal force</u> rather than the weight.)

QUIZ 4.13

Assume the kinetic frictional force between a 20 kilogram curling stone and the ice is 20 Newtons. A more massive stone (30 kilograms) is slid along the ice. What will be the frictional force on the 2nd stone?

________________ Newtons

(Answer: 30 Newtons)

Since the frictional force is proportional to the weight, this force will increase by 50% since the mass (and weight) of the 2nd stone is 50% greater.

Now imagine that the curling stone slid off the "sheet" (the ice) and onto a concrete floor. Do you think that the frictional force between curling stone and concrete would be the same as between curling stone and ice? Hopefully, your answer is "No". The frictional force depends on both the composition and roughness of the sliding object <u>and</u> of the surface underneath. These differences are indicated by assigning (generally from careful measurements) different **coefficients of friction** to different object/surface combinations (for the sliding case, we would actually talk about **coefficients of kinetic friction**). A greater coefficient of friction will result in a greater frictional force. Specifically, the kinetic frictional force is proportional to the coefficient of kinetic friction for that particular object-surface combination.

QUIZ 4.14

Rank the coefficients of kinetic friction of these sliding objects:

A Skis on hard-packed snow
B Rubber on dry concrete
C Rubber on wet concrete
D Steel on steel

Answer: B > D > C > A

Of course, when you are skiing you want the friction to be particularly low. Otherwise, this sport would not be very exciting. The fact that the coefficient of kinetic friction is greater for rubber on dry concrete than rubber on wet concrete (by about a factor of 3) is the reason that slamming on your brakes when driving on a wet road is more hazardous than on a dry road (a much greater stopping distance is needed in the wet road case).

So the kinetic frictional force is proportional to the normal force (the weight in simple situations) and to the coefficient of kinetic friction. Surprisingly, maybe, under standard conditions the kinetic frictional force does not depend on either the speed with which the object is traveling or the contact area between object and surface.

Next, when an object is moving but the motion does not involve the sliding of two surfaces, but rolling on some kind of tires or wheels, this is referred to as **rolling friction** and is characterized by a **coefficient of rolling friction**. How do you think rolling frictional force typically compares to kinetic frictional force?

QUIZ 4.15

For otherwise identical objects, which will generally be greater?

( x ) kinetic friction
( ) rolling friction

I hope you chose correctly. Rolling friction is generally quite small compared with kinetic friction. If that were not the case, a car would come to a stop rather quickly even without applying the brakes (also really bad gas mileage!) and the plane pull we watched earlier would be much more difficult (i.e. impossible!).

Finally, there is a third kind of friction called **static friction**. From the name you can probably guess that this applies to objects which are not moving (i.e. are static). When an object is *just about to start* sliding, the static frictional force is proportional to the normal force and its own **coefficient of static friction** similar to kinetic and rolling friction. In that case, the static frictional force is proportional to the coefficient of static friction and to the normal force. However, if the force applied to an object is relatively small (so the object is not on the verge of sliding), then the static frictional force will simply be equal to the applied force (equal in magnitude; opposite in direction).

Figure 4.3: Carolina Panther's Luke Kuechly pushing against a tackling sled

https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRiWYsHj1Ro-eM3v-eKQhxghCik9Z5sNdtn6xnnLUN4H15fU5Z18w

QUIZ 4.16

A football player pushes on a football tackling sled with a force of 350 Newtons but the sled does not move. What is the magnitude of the frictional force between the sled and the ground?

( ) greater than 350 Newtons
( ) less than 350 Newtons

( x ) equal to 350 Newtons
( ) more information is needed

We don't know in this case if the sled is on the verge of sliding or not. In either case, since it is not moving and assuming that there are no other forces involved in the direction of the push, it must be true that the pushing force is equal (in magnitude) to the frictional force.

In general, the maximum static frictional force will be *greater* than the corresponding kinetic frictional force for a given object-surface combination. This is the key to an important innovation in automobile braking - the anti-lock braking system (ABS). As the name implies, with ABS brakes the wheels do <u>not</u> lock but keep turning (but more slowly) to bring a car to a stop. Since the wheels are not sliding on the road, the frictional force at play is *static* friction <u>not</u> *kinetic* friction. So at times, friction can be a good thing! (Can you think of any other situations in which friction is "desirable"?)

A good example in which we can see friction at work is in the plane pulling video. Of course, there is rolling friction acting on the plane (as well as friction in the wheel bearings). We've already discussed the fact that the tension in the strap attached to the plane and to Mariusz is the force that moves the plane forward. But what is the force that moves Mariusz forward? Clearly Mariusz is pushing (very hard!) against the ground. But that is Mariusz exerting a force on the ground. What is the force(s) on Mariusz? There are the vertical normal force approximately equal to his weight and the tension in the rope. But those forces are not propelling him forward. It is the frictional force of the ground pushing back on Mariusz (which of Newton's Laws involves an opposing force of equal magnitude?) that causes him to move forward. Since he is not sliding, this would be static friction. In fact, it would be impossible for any of us to take even one step along the ground if there was no friction from the ground pushing us forward.

## Chapter 4 Homework

Questions

1. How many protons does an oxygen atom contain?

_____________ protons

Answer: 8 protons

2. The mass of an oxygen molecule is approximately 32 in a common physics unit (amu - "atomic mass unit"). For an oxygen molecule in the atmosphere of a planet where gravity is half as strong as on Earth, what will be the mass of an oxygen molecule in amu?

(A) 8 amu
(B) 16 amu
(C) 32 amu
(D) 64 amu

Answer: (C)

3. The mass of an oxygen molecule is approximately 32 in a common physics unit (amu - "atomic mass unit"). For an oxygen molecule in the atmosphere of Planet X, where gravity is weaker than the gravity on Earth, how will the weight of an oxygen molecule be affected?

(A) The weight will be the same.
(B) The weight will be less on Planet X.
(C) The weight will be greater on Planet X.

Answer: (B)

4. The gravitational force is reduced at higher elevations above the Earth's surface. Assume the World's Strongest Man competition is held in Denver, the "Mile High City". Compare the mass of a 120 kilogram Atlas Stone with the mass when the competition is held at sea level?

(A) The mass of the stone will be the same.
(B) The mass of the stone will be greater in Denver.
(C) The mass of the stone will be less in Denver.

Answer: (A)

5. The gravitational force is reduced at higher elevations above the Earth's surface. Assume the World's Strongest Man competition is held in Denver, the "Mile High City". How will that affect the Atlas Stone event as compared with the event when it is held at sea level?

(A) The Atlas Stone event will be easier in Denver than at sea level.
(B) The Atlas Stone event will be harder in Denver than at sea level
(C) The Atlas Stone event will be the same in Denver as at sea level

Answer: (A)

6. The gravitational force is reduced at higher elevations above the Earth's surface. Assume you pay the same price for a "quarter-pounder" in Denver, the "Mile High City" as you do at sea level. Compare these purchases.

(A) For the same price you get a "better deal" in Denver than at sea level.
(B) For the same price you get a "better deal" at sea level than in Denver.
(C) No difference in the deal between the two locations.

Answer: (A)

7. A football player pushes a training sled with a constant force of 700 Newtons. The sled slides across the rough ground with a constant speed. What kind of equilibrium is that?

(A) static equilibrium
(B) dynamic equilibrium
(C) The block is not in equilibrium.

Answer: (B)

8. A football player pushes a training sled with a constant force of 700 Newtons. The sled does not move under this force. What kind of equilibrium is that?

(A) static equilibrium
(B) dynamic equilibrium
(C) The block is not in equilibrium.

Answer: (A)

9. A football player pushes a training sled with a constant force of 700 Newtons. The sled accelerates under this force. What kind of equilibrium is that?

(A) static equilibrium
(B) dynamic equilibrium
(C) The block is not in equilibrium.

Answer: (C)

10. A football player pushes a training sled with a constant force of 700 Newtons. The sled slides across the rough ground with constant speed. What is the magnitude of the frictional force between the sled and the ground?

(A) 700 Newtons
(B) less than 700 Newtons
(C) more than 700 Newtons
(D) Not enough information is given.

Answer: (A)

11. A football player pushes a training sled with a constant force of 700 Newtons. The sled does not move under this force. What is the magnitude of the frictional force between the sled and the ground?

(A) 700 Newtons
(B) less than 700 Newtons
(C) more than 700 Newtons
(D) Not enough information is given.

Answer: (A)

12. A football player pushes a training sled with a constant force of 700 Newtons. The sled accelerates along the ground. What is the magnitude of the frictional force between the sled and the ground?

(A) 700 Newtons
(B) less than 700 Newtons
(C) more than 700 Newtons
(D) Not enough information is given.

Answer: (D)

13. A student gives a push to a rectangular block that sends it sliding across a rough table with the wider side in contact with the table. Once he releases it, the block comes to rest in 0.5 meters. Now he slides the block with the same force but with the narrow side of the block in contact with the table. What happens?

(A) The block travels further than 0.5 meters before stopping.
(B) The block travels less than 0.5 meters before stopping.
(C) No change - the block stops after 0.5 meters.

Answer: (C)

14. A student gives a push to a rectangular block that sends it sliding across a rough table. Once he releases it, the block comes to rest in 0.5 meters. Now he gives the block a more forceful push so that its initial speed is 50% greater than previously. Compare the frictional force in the two cases:

(A) The frictional force is greater for the slower moving block.
(B) The frictional force is greater for the faster moving block.
(C) The frictional force is the same.

Answer: (C)

15. A cyclist rounds a turn in the road at constant speed. What kind of equilibrium is that?

(A) static equilibrium
(B) dynamic equilibrium
(C) The bicycle is not in equilibrium.

Answer: (C)

16. A cyclist stops pedaling, which cause the bicycle to slow down. As the bicycle slows down, what kind of friction is acting between the bicycle and the road?

(A) static friction
(B) rolling friction
(C) kinetic friction
(D) No friction is acting on the bicycle.

Answer: (B)

17. A cyclist slams on her brakes which causes the wheels to stop rotating. As the bicycle slows down, what kind of friction is acting between the bicycle and the road?

(A) static friction
(B) rolling friction
(C) kinetic friction
(D) No friction is acting on the bicycle.

Answer: (C)

18. A cyclist slams on her brakes which causes the wheels to stop rotating. After the bicycle has come to a stop, what kind of friction is acting between the bicycle and the road?

(A) static friction
(B) rolling friction
(C) kinetic friction
(D) No friction is acting on the bicycle.

Answer: (D)

19. Two objects with the same mass and initial speed are sliding over different surfaces. Which object comes to rest first?

(A) a steel block sliding on a steel surface
(B) a ski sliding on snow
(C) a rubber block sliding on wet concrete

Answer: (A)

20. A student gives a push to a rectangular block, sliding it across a rough surface. The block comes to a stop after traveling for 2 meters. Now the student gives the same push to a block with twice the mass as before. What happens?

(A) The more massive block comes to a stop in less than 2 meters.
(B) The more massive block comes to a stop in more than 2 meters.
(C) The more massive block comes to a stop in 2 meters.

Answer: (A)

21. A curling stone has been given a push along the ice. After coming to rest, what forces are acting on the stone? Check all that apply:

(A) Static friction
(B) Kinetic friction
(C) Rolling friction
(D) Normal force
(E) Weight
(F) Tension
(G) Pushing force

Answers: (D), (E)

22. A curling stone is sliding down the ice while getting a push from behind by the player. What forces are acting on the stone? Check all that apply:

(A) Static friction
(B) Kinetic friction
(C) Rolling friction
(D) Normal force
(E) Weight
(F) Tension
(G) Pushing force

Answers: (B), (D), (E), (G)

23. A curling stone is sliding down the ice after getting a push from the player. What forces are acting on the stone? Check all that apply:

(A) Static friction
(B) Kinetic friction
(C) Rolling friction
(D) Normal force
(E) Weight
(F) Tension
(g) Pushing force

Answers: (B), (D), (E)

24. A curling stone is at rest on the ice. You push on the top of the stone, pressing it into the ice. What forces are acting on the stone? Check all that apply:

(A) Static friction
(B) Kinetic friction
(C) Rolling friction
(D) Normal force
(E) Weight
(F) Tension
(G) Pushing force

Answers: (D), (E), (G)

25. You push on a 20 kilogram curling stone with enough force so that it is sliding along the ice at constant speed. Now you repeat this with an additional 10 kilogram block placed on the stone. What happens?

(A) The stone goes faster than before.
(B) The stone goes slower than before.
(C) The stone does not move.
(D) Not enough information is given.

Answers: (D)

26. In discussing the plane-pulling video, Mariusz pushes back against the ground but it is the friction between ground and Mariusz that supplies the force that pushes him forward. Which of Newton's Laws accounts for this reaction force?
(A) 1st Law
(B) 2nd Law
(C) 3rd Law

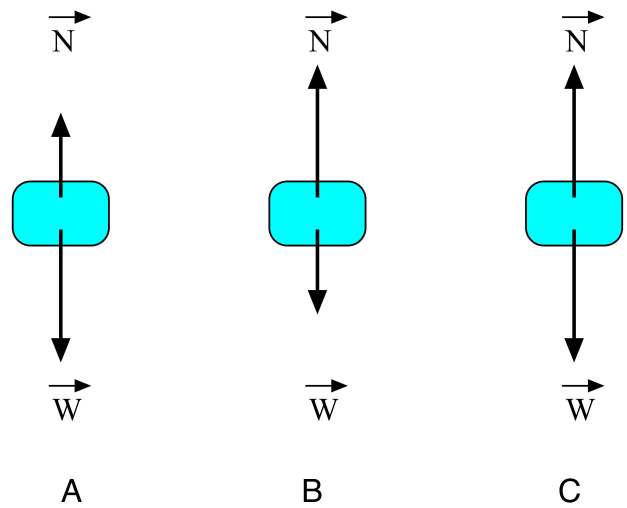
Answer: (C)

27. On Jupiter the gravitational force is ~2.5 times the gravitational force on Earth. Why is that?

28. With no changes, would the Atlas Stone event of the Moon's Strongest Man competition be more or less challenging than the same event on Earth? Explain.

29. What forces are involved in the "Pillars of Hercules" Strongman event? (Figure 4.1). (weight, normal force, tension)

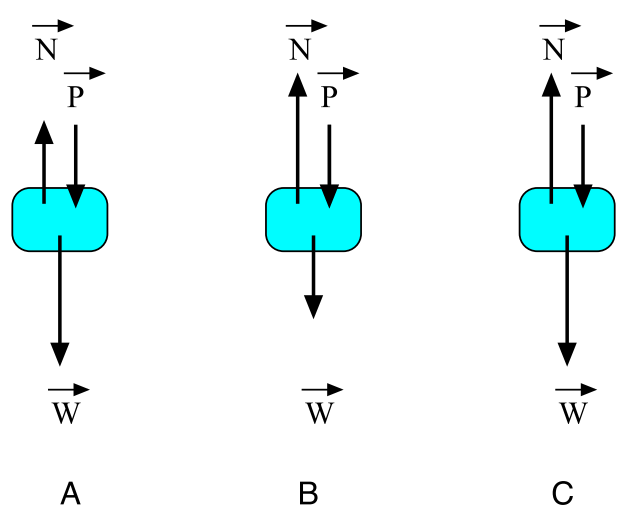
30. Besides the braking systems in cars, in what other situations is friction "desirable"?




31. A block is at rest on the floor. Which free body diagram best represents the forces on the block?

____________

Answer: (C)




32. A block is at rest on the floor. You push down on the top of the block with a pushing force, P. Which free body diagram best represents the forces on the block?

____________

Answer: (B)

## Exercises

1. What is the approximate mass of the men's 16 pound shot?

(A) 2 kilograms
(B) 4 kilograms
(C) 5 kilograms
(D) 7 kilograms
(E) 9 kilograms
(F) 10 kilograms

Answers: (D)

2. A 20 kilogram curling stone is at rest on the ice. What is the approximate weight of the stone?

(A) 20 kilograms
(B) 200 kilograms
(C) 10 Newtons
(D) 20 Newtons
(E) 100 Newtonst
(F) 200 Newtons
(G) 250 Newtons

Answers: (F)

3. A 20 kilogram curling stone is at rest on the ice. What is the approximate normal force acting on the stone?

(A) 20 kilograms
(B) 200 kilograms
(C) 10 Newtons
(D) 20 Newtons
(E) 100 Newtons
(F) 200 Newtons
(G) 250 Newtons

Answers: (F)

4. A 20 kilogram curling stone is at rest on the ice. You push the stone into the ice with a force of 50 Newtons. What is the approximate normal force acting on the stone?

(A) 20 kilograms
(B) 200 kilograms
(C) 10 Newtons
(D) 20 Newtons
(E) 100 Newtons
(F) 200 Newtons
(G) 250 Newtons

Answers: (G)

5. The acceleration given to a hockey puck by a force of 5 Newtons is 20 $m/s^2$ (ignore friction).
a. What is the mass of the puck?
b. If the force is increased to 8 Newtons, what will be the acceleration?

a. __________ kilograms

b. __________ $m/s^2$

Answers: 0.25 kilograms, 32 $m/s^2$,

On Jupiter the gravitational force is ~2.5 times the gravitational force on earth.
6. A 20 kilogram curling stone is carried to Jupiter. What is the mass of the curling stone on Jupiter?

(A) 8 kilograms
(B) 10 kilograms
(C) 20 kilograms
(D) 50 kilograms
(E) 200 kilograms

Answer: (C)

On Jupiter the gravitational force is ~2.5 times the gravitational force on earth

7. A 20 kilogram curling stone is carried to Jupiter. What is the weight of the curling stone on Jupiter?

(A) 200 Newtons
(B) 500 Newtons
(C) 1000 Newtons
(D) 2500 Newtons

Answer: (B)

8. A football player pushes on a football tackling sled which has a weight of 1000 Newtons with a force of 500 Newtons but the sled does not move. What is the magnitude of the frictional force between the sled and the ground?

(A) 200 Newtons
(B) 500 Newtons
(C) 1000 Newtons
(D) 2500 Newtons

Answer: (B)

9. A football player pushes a football tackling sled which has a weight of 1000 Newtons with a force of 500 Newtons but the sled does not move. What is the magnitude of the coefficient of static friction between the sled and the ground?

(A) 0.25
(B) 0.5
(C) 0.75
(D) 1.0
(E) 1.5
(F) 2.0
(G) Not enough information is given.

Answer: (G)

10. A football player pushes a football tackling sled which has a weight of 1000 Newtons with a force of 750 Newtons. The sled does not move but it is just about to start sliding. What is the magnitude of the coefficient of static friction between the sled and the ground?

(A) 0.25

(B) 0.5
(C) 0.75
(D) 1.0
(E) 1.5
(F) 2.0
(G) Not enough information is given.

Answer: (C)

11. A football player pushes a football tackling sled which has a weight of 1000 Newtons with a force of 500 Newtons. The sled slides along the ground with constant speed. What is the magnitude of the coefficient of static friction between the sled and the ground?

(A) 0.25
(B) 0.5
(C) 0.75
(D) 1.0
(E) 1.5
(F) 2.0
(G) Not enough information is given.

Answer: (G)

12. A football player pushes a football tackling sled which has a weight of 1000 Newtons with a force of 500 Newtons. The sled slides along the ground with constant speed. What is the magnitude of the coefficient of kinetic friction between the sled and the ground?

(A) 0.25
(B) 0.5
(C) 0.75
(D) 1.0
(E) 1.5
(F) 2.0
(G) Not enough information is given.

Answer: (B)

13. A football player pushes a football tackling sled which has a weight of 1000 Newtons with a force of 500 Newtons. The sled accelerates along the ground. What is the magnitude of the coefficient of static friction between the sled and the ground?

(A) 0.25
(B) 0.5
(C) 0.75
(D) 1.0
(E) 1.5
(F) 2.0
(G) Not enough information is given.

<u>Answer</u>: (G)

14. A football player pushes a football tackling sled which has a weight of 1000 Newtons with a force of 500 Newtons. The sled <u>accelerates</u> along the ground. What is the magnitude of the coefficient of static friction between the sled and the ground?

(A) less than 0.5
(B) equal to 0.5
(C) more than 0.5
(D) Not enough information is given.

<u>Answer</u>: (D)

15. A curler pushes a 20 kilogram curling stone along the ice with a force of 60 Newtons. Assuming the ice is frictionless, what is the magnitude of the acceleration of the stone?

__________ $m/s^2$

<u>Answer</u>: 3 $m/s^2$

16. A curler pushes a 20 kilogram curling stone along the ice with a force of 60 Newtons. Assuming the coefficient of kinetic friction between the ice and the stone is 0.2, what is the magnitude of frictional force on the stone?

__________ Newtons

<u>Answer</u>: 40 Newtons

17. A curler pushes a 20 kilogram curling stone along the ice with a force of 60 Newtons. Assuming the coefficient of kinetic friction between the ice and the stone is 0.2, what is the magnitude of the acceleration of the stone?

__________ $m/s^2$

Answer: 1 $m/s^2$

18. A football player pushes a football tackling sled which has a weight of 1000 Newtons with a force of 1000 Newtons. The sled slides along the ground with an acceleration of 0.5 $m/s^2$. What is the magnitude of the kinetic frictional force between the sled and the ground?

__________ Newtons

Answer: 500 Newtons

19. A football player pushes a football tackling sled which has a weight of 1000 Newtons with a force of 1000 Newtons. The sled slides along the ground with an acceleration of 0.5 $m/s^2$. What is the coefficient of kinetic frictional force between the sled and the ground?

__________

Answer: 0.5

20. In the weight room, a weightlifter holds onto a rope which is wrapped around a pulley. A 25 kilogram block is supported on the other end of the rope. The block is not moving.

a. What kind of equilibrium is that?

(A) static equilibrium
(B) dynamic equilibrium
(C) The block is not in equilibrium.

b. Find the tension in the rope.

__________ Newtons

Answers: a. (A) b. 250 Newtons

21. In the weight room, a weightlifter holds onto a rope which is wrapped around a pulley. A 30 kilogram block is supported on the other end of the rope. The strong man raises the rope, lowering the block to the floor at a constant speed.

a. What kind of equilibrium is that?

(A) static equilibrium
(B) dynamic equilibrium
(C) The block is not in equilibrium.

b. Find the tension in the rope. (Ignore any friction in the pulley.)

__________ Newtons

Answers: a. (B) b. 300 Newtons

22. In the weight room, a weightlifter holds onto a rope which is wrapped around a pulley. A 20 kilogram block is supported on the other end of the rope. The strong man lets go of the rope.

a. What kind of equilibrium is that?

(A) static equilibrium
(B) dynamic equilibrium
(C) The block is not in equilibrium.

b. Find the tension in the rope. (Ignore any friction in the pulley.)

__________ Newtons

Answers: a. (C) b. 0

# CHAPTER 5: Work and Energy


Steve Hooker of Australia in a pole vault competition

https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.australiantimes.co.uk%2Fsteve-hooker-soars-on-mixed-day-for-australian-olympians%2F&psig=AOvVaw1WrreSTe_3eTBXKmWPX8JD&ust=1594483884340000&source=images&cd=vfe&ved=0CAIQjRxqFwoTCJiKyMaJw-oCFQAAAAAdAAAAABAE


VIDEO 5.1: The gold medal-winning performance of Steve Hooker of Australia at the 2008 Olympics

https://digitalcommons.uri.edu/physicsofsports/21/

Select and watch VIDEO 5.1.

## 5.1: Kinetic Energy

In the video opening this chapter you watched the gold medal-winning pole vault of Steve Hooker from Australia at the 2008 Summer Olympic Games in Beijing. Before we talk more about this event, let's use our conversion skills.

QUIZ 5.1

In the pole vault you just watched, Steve Hooker cleared the bar at a height of 5.96 meters. Approximately how many feet is this?

( ) 13 feet
( ) 15 feet
( ) 17 feet
( x ) 19 feet
( ) 21 feet

If you remembered that a meter is slightly more than a yard, 3 feet, the best answer is 19 feet (the true conversion is 19.55 feet).

Thinking about the video, we can break the performance into several parts:

1. The "approach" - the run of the "vaulter" along the "runway" before the pole is "planted."
2. The planting of the pole and "takeoff" in which the pole bends considerably.
3. The "swing up" and "extension" in which the vaulter reaches his or her maximum height.
4. The drop back down to the landing mat.

By now, you should not be surprised to learn that there is a lot of physics in this process. The pole vault is an excellent example of the conversion of energy from one form to another. We are all familiar with various forms of energy in our everyday world, from energy to propel an automobile, heat a home, generate electricity. And you have no doubt heard something about solar energy, atomic energy, and other forms as well. There are many different forms of energy though we will only need to consider a relatively few in our examination of the physics of sports.

Back to the pole vault. First the vaulter runs faster and faster along the runway. This is an example of our first form of energy - the energy of motion called **kinetic energy**, usually labeled, K. Kinetic energy depends on the mass and the speed of an object. Not surprisingly, the greater the speed of an object, the greater its kinetic energy. What do you think about the role of mass?

QUIZ 5.2

Consider two athletes running at the same speed. The mass of runner 1 is greater than the mass of runner 2. Which has the greater kinetic energy?

( x ) Runner 1
( ) Runner 2
( ) The kinetic energy will be the same for both.

The more massive runner has the greater kinetic energy. Hopefully this makes sense. For example, let's consider a block (block 1) that is twice the mass of block 2. Assume both blocks are traveling at the same speed, v. But, as illustrated in the sketch below, we could think of block 1 is being composed of two block 2's glued together. So shouldn't the kinetic energy of block 1 be twice the kinetic energy of block 2? Yes!

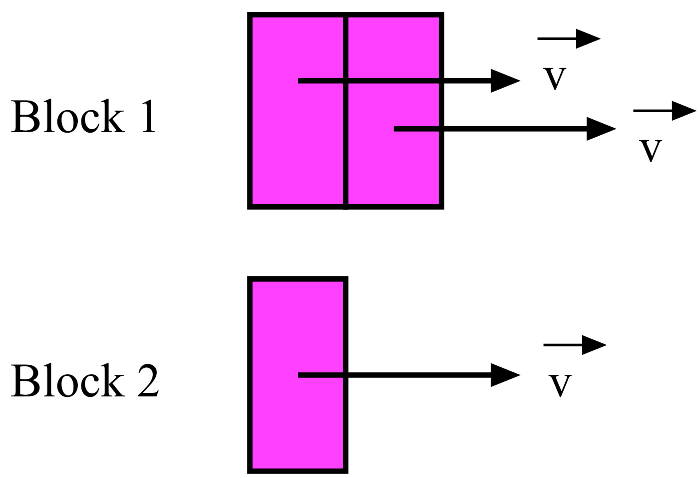



FIGURE 5.1: Sketch of two blocks with the same velocity but different masses

This means that kinetic energy is proportional to the mass. What about speed? If we double the speed of an object, do we double the kinetic energy? Makes sense (maybe?) but the answer is "No." We would instead quadruple the energy since the kinetic energy scales as the square of the speed. Putting this together,

$$K = \frac{1}{2}mv^2 \qquad \text{Equation 5.1}$$

QUIZ 5.3

The kinetic energy of a (slowly) moving Atlas stone is 10 Joules (J). If a stone with twice the mass is moved with the same speed, what is the kinetic energy of the stone?

( ) 5 Joules
( ) 10 Joules
( ) 15 Joules
( x ) 20 Joules
( ) 40 Joules

Note: The SI unit of energy is the Joule, abbreviated J, named for James Prescott Joule who did some important early work concerning heat and energy. The Joule is shorthand for the combination of units (kilogram times (meter/second) squared). Where does this unit combination come from?

QUIZ 5.4

The kinetic energy of a moving Atlas stone is 10 Joules (J). If the speed of the stone is doubled with no change in mass, what is the kinetic energy of the stone?

________________ Joules

(Answer: 40 Joules)

In the opening video, we watched Steve Hooker in his gold medal vault. Hooker's mass is 85 kilograms; the mass of a pole is approximately 5 kilograms. As an estimate if we take his final speed as 10 meters per second (an upper limit). That makes the kinetic energy of Hooker plus pole at the end of his approach as:

$$K = \frac{1}{2}(85\,\text{kg} + 5\,\text{kg})(10\,\text{m/s})^2 = 4500\,\text{J}$$

Where does that energy come from and what happens to it? We'll address these questions in the next sections.

## 5.2: Elastic Energy

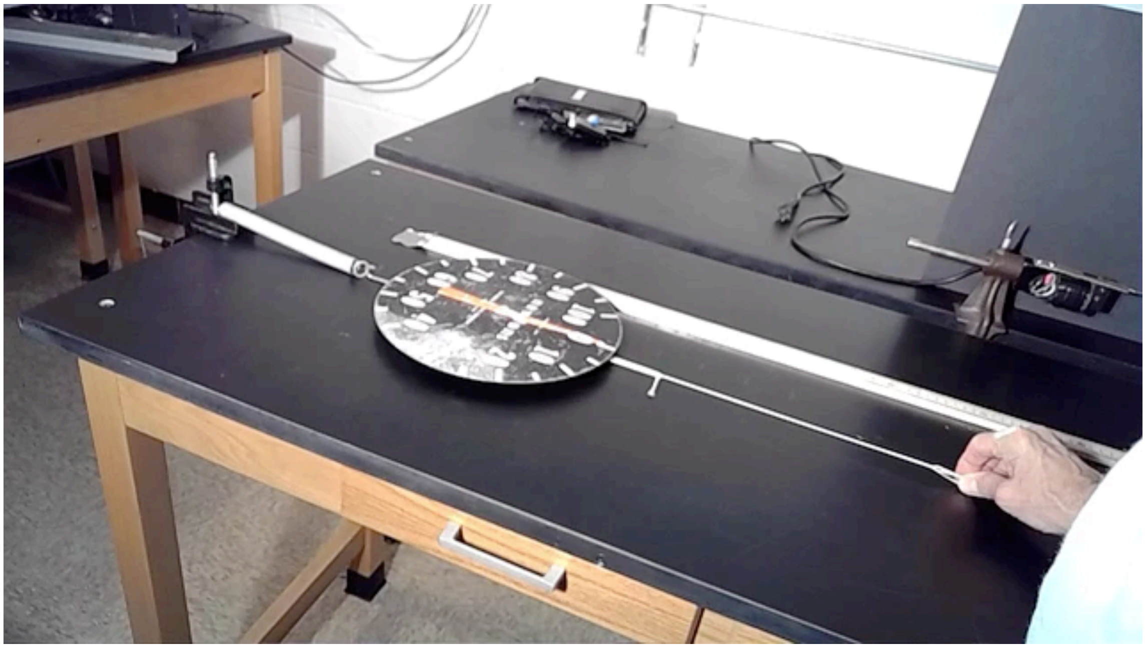
At the end of the approach, Steve Hooker almost stops moving forward, so his kinetic energy becomes nearly 0, with the result that the pole bends considerably. So it might seem reasonable to think that the kinetic energy he had built up during the approach in some sense is transferred to the bend in the pole. From a physics point of view, this is exactly what happens.

An extremely important fundamental law of physics is the **Law of Conservation of Energy** which states that the total energy of a system is conserved; it can nether be created nor destroyed. That doesn't mean that it is always easy to identify and account for all the kinds of energy that are involved in a complicated process. However, in most applications that we have in mind, such as the pole vault and others we will discuss later, we can come close.

So ideally, almost all of the kinetic energy of Hooker's approach was transformed into the energy we want to associate with the bend in the pole. This energy, which is a kind of *stored* energy is one example of **Potential Energy**, often labeled U. There are several forms of potential energy we will deal with in this course. The energy associated with the bend in the pole is called **elastic potential energy**. A standard example of stored elastic energy that is encountered in almost all introductory physics courses is the energy stored in a stretched or compressed spring. We'll talk about that now.

There are many devices and objects in the everyday world that contain springs or have properties that are similar to the properties of springs. We'll consider a few in the sports world. Simple springs are "simple" - they obey particularly simple equations for force and energy. As a result, they are examined in a variety of physics courses.

Now we'll take a look at a video (VIDEO 5.2) that illustrates the force that a spring exerts as it is stretched. In this video, a spring is attached to a force meter and is then stretched by various amounts. The force meter gives the force exerted by the spring. Note the forces and fill in the table below. I stopped pulling briefly for every 10 cm of stretch.



VIDEO 5.2: Stretched spring vs. applied force

https://digitalcommons.uri.edu/physicsofsports/22/

QUIZ 5.5

| Step | Distance (cm) | Force (N) |
|---|---|---|
| 0 | 0 | |
| 1 | 10 | |
| 2 | 20 | |
| 3 | 30 | |
| 4 | 40 | |
| 5 | 50 | |

The table below is what I came up. How does that compare to yours?

| Step | Distance (cm) | Force (N) |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 10 | 2 |
| 2 | 20 | 4 |
| 3 | 30 | 6 |
| 4 | 40 | 9 |
| 5 | 50 | 13 |

TABLE 5.1: Stretched spring vs. applied force

Hopefully you can see the trend that the force of the spring scales (more or less) linearly with the amount of stretch. (If you stretch a spring too much, this relationship doesn't hold as well anymore.) Other factors that affect the force of a spring is the nature of the spring itself: what is it made of, is it tightly or loosely wound, what is the diameter of the spring, ... All of these issues are related to how "stiff" the spring is. We characterize the stiffness of a spring by its **spring constant**, k. How do you think the stiffness of a spring will be related to the force a spring exerts when it is stretched?

QUIZ 5.6

For a stiffer spring, what can we say about the force the spring exerts when it is stretched?

( ) The force of a stiffer spring will be less.
( x ) The force of a stiffer spring will be greater.
( ) The force of a stiffer spring will be unchanged.

Hopefully you chose correctly. The force (in magnitude) is given by the expression:

$F = kx$ Equation 5.2

where x is the stretch of the spring and k is the spring constant.

This equation couldn't be much simpler. If a spring is compressed instead of stretched, the expression for the (magnitude of the) force will be the same with x giving the amount of compression.

From step 3 in Table 5.1, I would estimate the spring constant of the spring in VIDEO 5.2 to be ~(6N)/(0.3m) = 20 N/m. (Note that we converted a stretch of 30 cm to 0.3 m.)

The potential energy stored in a spring, $U_{spring}$ , when it is either stretched or compressed is given by an expression quite similar to the force equation above:

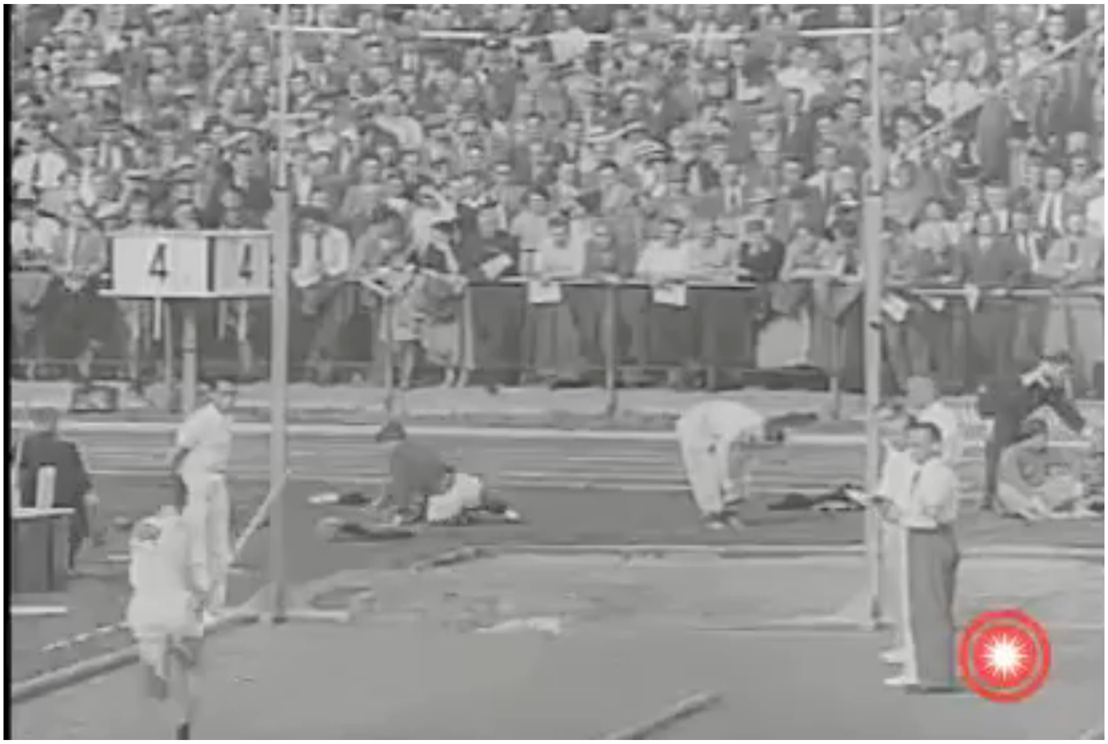
$$U_{spring} = \frac{1}{2}kx^2 \qquad \text{Equation 5.3}$$

Now let's apply these ideas to the pole vault. Clearly the pole has a stiffness and presumably different poles have different stiffnesses which will depend on the material from which the pole is made, the diameter of the pole, the length, and probably other factors as well, just as various factors determine the spring constant of a spring. Pole vault aficionados talk about the "flexibility" of poles rather than stiffness and characterize a pole by its "flex number". The flex number is the amount (in centimeters) by which a pole bends when its two ends are fixed and a mass is suspended from the center (how large a mass I don't know, though that's obviously important).

Similar to the stretch or compression of a spring, a pole vault pole bends (quite a lot in the video we watched). This combination of flex number or some measure of stiffness and "amount of bend", however that is exactly measured, will result in elastic potential energy stored in the bent pole very similar to the potential energy of a stretched or compressed spring.

So the pole used in pole vaulting must be strong enough to support the weight of the vaulter, it should be as light as possible (why do you want the pole to be as light as possible?), and it should be able to bend in order to store elastic energy. I would expect that there is a fair amount of technology going into this sport. This suggested a question to me that I thought would be interesting to research - what was pole vaulting like and what were the vaulting heights like many years ago? I hope you would agree with me that pole vaulting world records have probably increased as time goes on (how does such a world record decrease anyway?) but by how much? and can we see why?

Now let's take a look at a pole vaulting event from 1936, near the beginning of TV broadcasting (VIDEO 5.3). You will see a clip from the German National Track and Field Championships which were held in Berlin in that year. I want you to look for differences compared with a modern pole vault like the one we watched earlier. Of course you will see many differences - the video is in black-and-white, the outfits are not "stylish" by today's standards, the vaulter lands in a sand pit instead of a nice big piece of foam. (Why can he get away with that in this early event and not so well in today's competitions?)



VIDEO 5.3: Pole Vault of Julius Muller at the 1936 German National Track and Field Championships

https://digitalcommons.uri.edu/physicsofsports/23/

Maybe you noticed the height the vaulter cleared. Remember that Steve Hooker's gold medal vault was just short of 6 meters (how many feet is that?). What I really want you to make a note of is the flexibility of the pole. For purposes of comparison, I include below an image from another one of Steve Hooker's vaults.


FIGURE 5.2: Steve Hooker of Australia in a pole vault competition

http://en.people.cn/mediafile/200808/23/P200808231721022145223983.jpg

QUIZ 5.7

In the pole vault you just watched (VIDEO 5.3), compare the bend in the pole to the bend in the modern poles.

( ) The amount by which the pole bends is pretty much the same in 1936 and 2008.
( ) The amount by which the pole bends is greater in 1936 than in 2008.
( x ) The amount by which the pole bends is less in 1936 than in 2008.

I'm sure you will agree that there was a big difference. So the modern pole bends much more (due to modern technology mainly) so the amount of elastic energy it stores will be greater. Other factors aside, I would expect that this would result in a substantial increase in pole vaulting world records through the years. It certainly looks from the video that the height of the bar in 1936 was a lot less than in 2008. Remember that Steve Hooker's gold medal winning height was just under 6 meters; the current world record held by Sergey Bubka from the Soviet Union/Ukraine is 6.15 meters. Of course the 1936 video was from a national championship, not an international one. The world record from that year was a height of 4.43 meters set by George Varoff of the U.S. So there really is a significant difference between then and now. I think it would be interesting to plot the pole vaulting records vs. year to examine this trend in more detail, and maybe relate that to changes in pole technology.

I've thought of a few other examples of elastic energy in sports, as illustrated below. Can you think of any others?

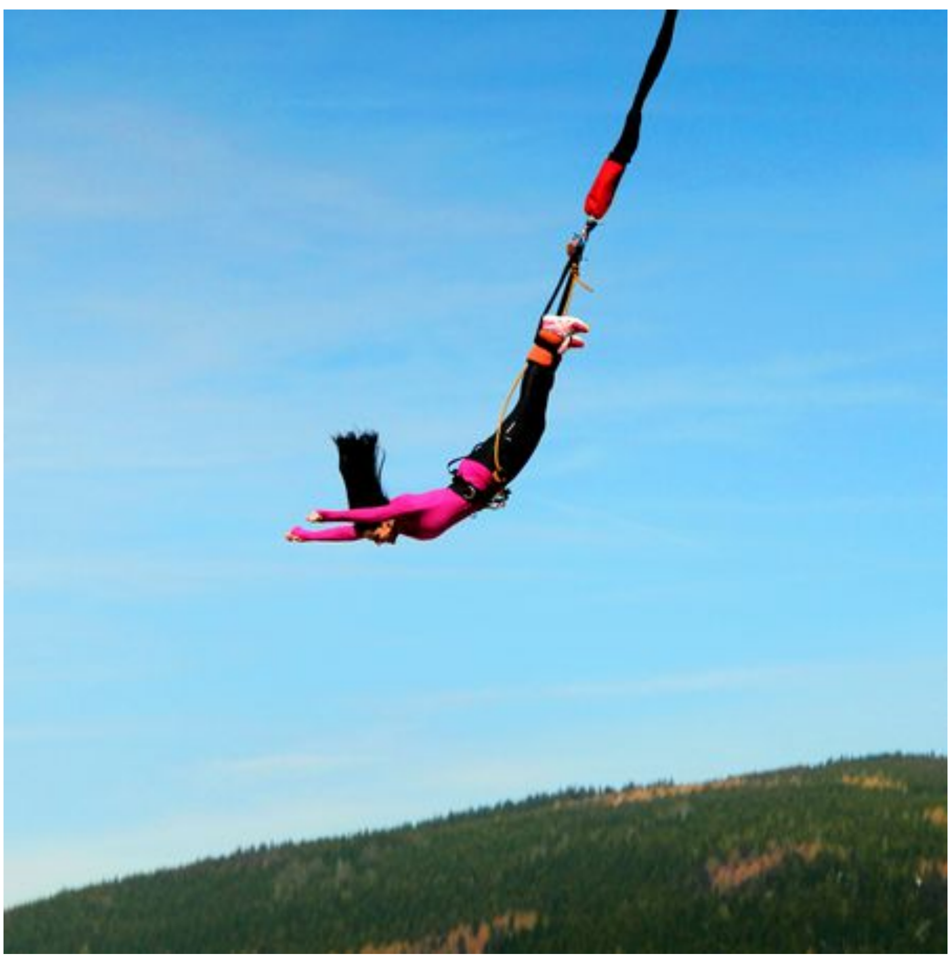


FIGURE 5.3:
Bungee Jumper

https://enjoyprague.net/media/CACHE/images/images/IMG_7255-2/5757655cf7b1f9695a9ed4deb756ba10.jpg


FIGURE 5.4:
Archery

https://media.gettyimages.com/photos/archery-picture-id171588296

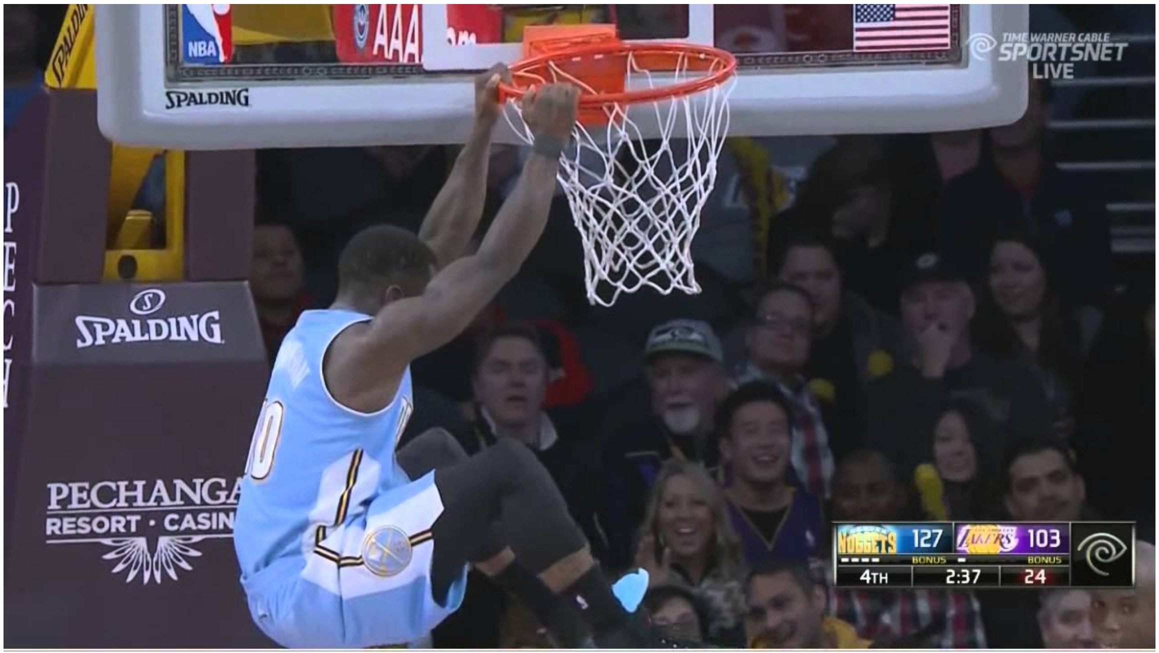



FIGURE 5.5:
Nate Robinason "Hanging on the Rim"

https://i.ytimg.com/vi/1x-Gxm3wz-k/maxresdefault.jpg

Getting back to the pole vault, first the vaulter generates as much kinetic energy as possible, then that kinetic energy is converted into the elastic energy of the bent pole. Obviously, the vaulter wants to convert as much of his kinetic energy into elastic potential energy as possible. How much will depend on the quality of the pole, the technique of the vaulter, and other factors. Now for the next step: the vaulter "swings up."

## 5.3: Gravitational Potential Energy

At the end of the swing up, the pole has straightened out again, the vaulter is at his maximum height, and he has more or less stopped moving. Therefore, the elastic potential energy in the pole and the kinetic energy of the vaulter are both close to zero. So if energy is conserved, where has it gone? There must be another form of energy that we haven't discussed yet. Yes! - There are actually many other forms of energy that we haven't discussed yet (and won't in this book). The form of energy we consider next is the energy associated with a change in height. This is also a type of stored or potential energy and is known as **gravitational potential energy**.

Stored how? In the case of Steve Hooker in the video we watched earlier, he reaches a highest point of ~six meters and stops momentarily. But then he will fall back down, generating an increasing amount of kinetic energy. While he stopped at six meters he has "stored" gravitational potential energy.

Remember for the spring that there was a relatively simple equation for the potential energy which was similar to the force equation for the spring. The same is true for gravitational potential energy. Recall that the force due to gravity (also called the weight, W) is given by:

$W = mg$ Equation 4.1

The potential energy due to gravity, $U_{grav}$ , is given by the equation:

$U_{grav} = mgh$ Equation 5.3

where h is the change in height. We can measure the height of an object from any reference point (well, not quite – more on this later.). It is only the change in height that matters in determining the gravitational potential energy (really the *change* in gravitational potential energy).

QUIZ 5.8

A bowling ball with weight 80 Newtons is raised by a height of 0.5 meters. What is the change in gravitational potential energy of the bowling ball?

________________ Joules

(Answer: 40 Joules)

Remember that the SI unit of energy is the Joule (for all types of energy).

Let's calculate the approximate gravitational potential energy of Steve Hooker at the top of his trajectory using the mass of Hooker of 85 kilograms (now we won't include the mass of the pole; is this correct - not completely; why not?), a height change of 6 meters (what about that height - any problems with that? - see later chapters), and $g \sim 10$ m/s$^2$:

$$U_{grav} = mgh = (85\,\text{kg})(10\,\text{m/s}^2)(6\,\text{m}) = 5100\,\text{J}$$

That is a little greater than our estimate for Hooker's kinetic energy (4500 J) from the first section of the chapter, but it is not too bad. I think we could improve on this estimate and get closer to 4500 J with a little more thought but it's good enough for now.

After the vaulter reaches his or her highest point, there is a little more pushing and body motion to get over the bar, but basically the vaulter then falls back down, converting gravitational energy back to kinetic energy before the vaulter hits the mat and eventually comes to rest. That energy is not lost but is converted to other forms of energy including sound and mainly heat. Energy is always conserved though in the real world it is often difficult to keep track of every Joule of it.

## 5.4: Calories

FIGURE 5.6:
Big Mac (with cheese)

http://www.foxnews.com/images/305672/1_61_Big_Mac.jpg

Maybe you can now see that from a physics point of view, the pole vault is an exercise in converting kinetic energy into elastic potential energy and then into gravitational potential energy (and back into kinetic energy and then heat and sound). Ideally, the vaulter would like to convert all of his or her kinetic energy into gravitational potential energy. That will produce the greatest vault height since the mass and $g$ are the only other factors in determining the gravitational potential energy. How well the vaulter is able to make this conversion (scientists would call this the "efficiency" of the process, and maybe athletes as well?) will depend quite a lot on the vaulter's technique as well as on the quality of the pole that temporarily stores the kinetic energy as elastic energy.

What about the kinetic energy? Where did it come from? The vaulter starts the event at rest so if energy is conserved, the energy had to come from another form. The original source of this energy, as you probably guessed, is the physiological "burning of calories" that the vaulter's body carried out during the approach. This form of energy is chemical or biochemical in nature and not really the subject of this course, but we do want to relate it to what we know and have learned.

**Calories** - we've all heard of them frequently in talking about good and bad foods, exercise, etc. The calorie is a unit of energy like the Joule. These units can be converted back and forth. In particular, one calorie of energy is approximately equal to four Joules of energy (more exactly, 1 calorie = 4.184 Joules).

Since we had estimated that Steve Hooker had approximately 4500 Joules of kinetic energy at the end of his approach, then he had to burn ~4500 Joules which is ~ 1100 calories during his approach. Right? Not quite. We should remember that during physical exertion, something else happens to your body. What is it? (Think running on a treadmill or taking a spin class or an aerobic class for one hour). Yes, your body heats up. So burning calories generates (unwanted) heat as well, so your body in general will need to burn extra calories to perform some physical feat like a pole vault. How much extra? I don't know though I'm sure you can learn more by doing some research. I do know that one goal of an athlete through training is to be able to maximize the conversion of calories burned to the kinetic energy generated (or whatever form of energy is needed, depending on the sport) - another kind of efficiency.

Back to calories. We encounter them in food products quite often. You eat food to take in calories, then you (hopefully) burn them up later in some kind of physical exertion. How many calories? How much physical exertion? Let's talk Big Mac. How many calories do you gain by consuming a Big Mac?

QUIZ 5.9

Approximately how many calories do you gain by consuming a Big Mac?

| | |
|---|---|
| (  ) | 200 calories |
| (  ) | 300 calories |
| (  ) | 500 calories |
| (  ) | 700 calories |
| ( x ) | None of the above |

That was a trick question. We'll learn why in a minute. (Curious? Are you wondering if the answer is higher or lower?) First, let's assume that the correct answer is that a Big Mac contains 500 calories (not true).

QUIZ 5.10

Assuming (incorrectly) that a Big Mac contains 500 calories, how many Big Macs would Steve Hooker have to eat to generate enough energy (~1100 calories) to make his pole vault approach (round off your answer to the nearest number of Big Macs)?

_______________ Big Macs

(Answer: 2 Big Macs)

Do you think that 2 Big Macs is reasonable? Seems too high to me. It is.

Sometime in the past for whatever reason, scientists or maybe food product executives came up with a different calorie unit - the kilocalorie, also called a "Food Calorie," which is 1000 calories, abbreviated as Kcal or Cal with a big "C". This is the calorie unit we always see on food packaging, etc. So you might see a Big Mac (with cheese) listed as having ~700 Calories. That means you actually gain 700,000 (scientific) calories when you consume it! That means that if Steve Hooker ate a Big Mac before one of his competitions (doubtful!) he would gain enough energy to make (700,000)/(1100) ~ 635 vaults! So you can see that's it's not so easy to burn off those Big Mac calories! It takes a lot of work - our next topic.

Before we get to that, let's consider the calorie consumption in some other sports.

QUIZ 5.11

Rank the amount of Food calories burned per hour for the following sports:

A Shuffleboard
B Running at 7.5 mph (8 minute per mile pace)
C Football
D Basketball

Answer: B > D > C > A

Did you get the ranking correct? Below I've included the Food calories "burned" or used per hour (by a 155 pound athlete) for those and a few other sports as well.

| **Sport** | **Food calories burned per hour (155 lb athlete)** |
|---|---|
| Cycing (racing at >20 mph) | 1126 |
| Running at 7.5 mph | 950 |
| Boxing | 844 |
| Rugby | 704 |
| Swimming laps (fast) | 704 |
| Cross country skiing | 633 |

| | |
|---|---|
| Football | 633 |
| Hockey | 563 |
| Basketball | 563 |
| High impact aerobics | 493 |
| Bowling | 211 |
| Shuffleboard | 211 |

Source: www.nutristrategy.com/caloriesburned.htm

Any surprises? I would not have put boxing so high and would have expected cross country skiing to be ranked higher?!

Speaking of calories, here's a typical breakfast of gold medal-winning swimmer Michael Phelps when he was training for the Olympics in 2008 (see Chapter 1): three fried egg sandwiches with cheese, lettuce, tomatoes, fried onions, and mayonnaise; two cups of coffee; one five-egg omelet; one bowl of grits; three slices of French toast topped with sugar; and three chocolate chip pancakes. "You can eat whatever you like", he explained, "as long as it adds up to 12,000 calories a day!" (That would be 12 million scientific calories - not recommended for most of us!)

## 5.5: Work

Another way to consider various forms of energy is to examine the **work** done in a physical process. Work is not a form of energy (though it has the same units - Joules) but when work is done, energy is converted from one form to another. Now we are familiar with the concept of work in our everyday world. As examples: "It took a lot of work to help my friend carry his piano up to his 3rd floor apartment." "I worked hard to finish last week's homework assignment on time." "It took more work than I expected to hold up this box of books until the bus showed up." And I'm sure you can think of many other examples.

You might expect that in physics when we talk about work we have something much more specific in mind than those examples above. By work, W, we specifically mean force times distance, or as an equation (in simple situations):

$W = Fd$ Equation 5.4

Unfortunately, we also used "W" for weight. Oh well, we'll try to keep them straight. Now d refers to the distance an object is moved and F is the net force parallel to the direction of motion. So as you can see our physics definition of work is quite specific. In fact, of the three examples for "work" in the everyday world, only one will be work in the physics sense? Which one?

QUIZ 5.12

Which of these three examples corresponds to non-zero work in the physics sense of the term?

( x ) It took alot of work to help my friend carry his piano up to his 3rd floor apartment.
(   ) I worked hard to finish last week's homework assignment on time.
(   ) It took more work than I expected to hold up this box of books until the bus showed up.

Only in the first example was an object (the piano) actually moved some distance. I'm not saying that you wouldn't burn calories holding up a box of books or even doing your homework, but these activities would not generate any work in the physics sense.

Let's apply our new understanding of work to a few sports examples we have already considered. First, remember the plane pulling event from the World's Strongest Man Finals. That plane weighed 88,000 pounds (~19,600 Newtons; mass ~ 1960 kilograms) and Mariusz Pudzianowski pulled it a distance of 25 meters. So to get the work done by Mariusz on the plane do we multiply (19,600 Newtons) by (25 meters)?

Hopefully, you're thinking "No" since the weight does <u>not</u> act in the direction of the motion of the plane. We would need to know the actual force he exerted to calculate the work done by Mariusz using Equation 5.4. If we knew the final speed we could calculate the net work done on the plane since the work done was converted into kinetic energy. We still wouldn't know the work that Marisuz did himself since other forces are involved, particularly various forms of friction that he had to overcome.

Let's turn to another example from Chapter 4 - the Atlas Stone Competition. As a reminder, I've included an image from a competition below:

FIGURE 5.7: Brian Shaw of the U.S. in the Atlas Stone event of the World Strongest Man competition

https://www.flickr.com/photos/tvnewsphoto/2859110936/in/photostream/

Let's calculate/estimate the work done by an athlete in lifting an Atlas stone and placing it on its stand. We'll use 120 kilograms as the mass of one of the stones. The stands are about head height, ~ 6 feet; let's use 2 meters. The force the athlete must apply to the stone to lift one must be at least equal to the weight of the stone. We'll use the weight as the force applied. Therefore, the work done is:

W = weight x distance = $(120\,\text{kg})(10\,\text{m/s}^2)(2\,\text{m}) = 2400\,\text{J}$

Again this is just an estimate since we didn't measure the height very carefully, and we also ignored the fact the stone was moving before being placed on the stand so it had some kinetic energy, though probably quite small compared to the work we calculated.

Let's check our understanding of work:

## QUIZ 5.13

You push a curling stone with a force of 5 Newtons over a distance of 3 meters. How much work do you do on the stone?

( ) 5 Joules
( ) 10 Joules
( x ) 15 Joules
( ) 20 Joules
( ) 30 Joules
( ) 60 Joules

## QUIZ 5.14

Now you push a curling stone of double the mass from the previous example with a force of 5 Newtons over a distance of 3 meters. How much work do you do on the stone?

( ) 5 Joules
( ) 10 Joules
( x ) 15 Joules
( ) 20 Joules
( ) 30 Joules
( ) 60 Joules

Same answer in both cases. The weight of the second stone is twice as great but as for the plane pull, the force of gravity (the weight) is <u>not</u> in the direction of motion of the stone. The pushing force is still 5 Newtons so the work done is the same.

## 5.6:  Friction

You just had a couple of quizzes about the kinetic energy of a curling stone. Select VIDEO 5.4 and we'll watch again (!) the curling video from Chapter 1.


VIDEO 5.4:  Segment of the curling competition from the 2010 Winter Olympics

https://digitalcommons.uri.edu/physicsofsports/24/

The curler pushes the stone for a while, doing work on the stone and giving it kinetic energy. But then in the video, the stone eventually comes to rest (or almost to rest before it is removed from play).  What happened to the kinetic energy? Is energy still conserved? I think you can guess why the stone slowed down to a stop.

QUIZ 5.15

What caused the curling stone to come (almost) to rest?

(   )   Mass of the stone
(   )   Weight of the stone

(   )   Change in height of the stone
(   )   Gravitational potential energy of the stone
( x )   Friction

Probably you knew that friction slowed the stone down. Even on the ice there is still some friction. In fact, one of the functions of the "sweepers" in curling is to sweep the ice in front of the stone as it travels in order to reduce the friction. This is also an example of one of Newton's Laws (which one?) regarding the natural state of a moving object.

But friction is a force, it is not a form of energy so we still haven't completely answered the question of how energy is conserved as the kinetic energy of the stone decreases. But since friction is a force it can do work, and that is exactly what happens. The force of friction does work on the stone, the work done being equal to the <u>frictional force (kinetic friction) times the sliding distance</u>, and this work converts the kinetic energy into other forms of energy.

What forms? Well, what happens when you rub two objects together (such as your hands when you come in from the cold)? Heat happens. Friction converts the kinetic energy of the stone (primarily) into heat. So energy is still conserved, though the new form of energy is harder to measure. Can you think of any other sports examples like this? Remember that the object must be sliding for kinetic friction to have an effect.

# 5.7: Power

In the Atlas Stone video we watched in Chapter 4, Brian Shaw lifted 6 Atlas Stones and placed them on 6 stands. Let's say the work we calculated per stone in the last section was about right (we'll round up to 2500 Joules per stone). In that case, Brian did approximately 6 x 2500 J = 15,000 Joules or 15 kiloJoules (kJ) of work. He got that energy by burning at least that many calories. But he didn't win that event by exerting 15 kiloJoules of work/energy. He won by doing that in the least amount of time (27.11 seconds to be exact).

This kind of situation made it clear to scientists at some point in the past that it can be useful and important to measure and calculate energy and work done per time, or the rate of work being done. In physics we call this **power**, P, and in simple cases power is simply given by dividing work or energy by time:

$$P = W/t \qquad \text{Equation 5.5}$$

The SI unit is the Joule per second, which has been given a new name of the "Watt" named after James Watt who invented the steam engine.

We are also familiar with "power" and "watts" in our everyday world. For example, the power of a car engine (usually given in horsepower - an American unit of power) or the power of a stereo system (given in Watts generally). These are both consistent with the physics definition of power. The power rating of the car engine is a measure of the ability of the engine to do work in a certain amount of time. The power of the stereo is the energy per unit time it is capable of outputting.

We'll finish the chapter by estimating the power of Brian Shaw in the Atlas Stone event. We have an estimate of the work done and the time (we'll round up to 30 seconds), so the calculation should be straightforward:

QUIZ 5.16

Approximately what was the average power of Brian Shaw in the Atlas Stone event??

( ) 50 Joules
( ) 500 Joules
( ) 5000 Joules
( ) 50 Watts
( x ) 500 Watts
( ) 5000 Watts

Now doing that calculation wasn't too much "work", was it?

## Chapter 5 Homework

Questions

1. A cyclist is riding down a straight road at constant speed. What is the energy associated with the motion of the cyclist?

(A) Kinetic Energy
(B) Elastic Energy
(C) Gravitational Potential Energy
(D) Heat generated by friction

Answer: (A)

2. An archer pulls back the string of her bow. What is the energy associated with the stretched string?

(A) Kinetic Energy
(B) Elastic Energy
(C) Gravitational Potential Energy
(D) Heat generated by friction

Answer: (B)

3. A tennis ball collides with a tennis racket, causing the strings in the racket to be momentarily stretched? What is the energy associated with these stretched strings?

(A) Kinetic Energy
(B) Elastic Energy
(C) Gravitational Potential Energy
(D) Heat generated by friction

Answer: (B)

4. A ski lift carries skiers and deposits them at the top of a mountain? What is the energy associated with change in height of the skiers?

(A) Kinetic Energy
(B) Elastic Energy
(C) Gravitational Potential Energy
(D) Heat generated by friction

Answer: (C)

5. A cyclist is riding down a straight road at constant speed. He squeezes the brakes and the bicycle comes to a stop. Is energy conserved?

(A) Yes
(B) No

Answer: (A)

6. A cyclist is riding down a straight road at constant speed. He squeezes the brakes and the bicycle comes to a stop. Is kinetic energy conserved?

(A) Yes
(B) No

Answer: (B)

7. A cyclist is riding down a straight road at constant speed. He squeezes the brakes and the bicycle comes to a stop. In what form does the energy end up?

(A) Kinetic Energy
(B) Elastic Energy
(C) Gravitational Potential Energy
(D) Heat generated by friction

Answer: (D)

8. Sometimes before taking a shot a hockey player "preloads" his stick which means that he bends it back by dragging it along the ice before hitting the puck? What is the energy associated with this preloading?

(A) Kinetic Energy
(B) Elastic Energy
(C) Gravitational Potential Energy
(D) Heat generated by friction

Answer: (B)

9. A block is hanging from a spring, which causes the spring to be stretched by 0.2 meter. If a stiffer spring were used, what would be different?

(A) There would be no change in the stretch of the spring.
(B) The stretch of the spring would increase.
(C) The stretch of the spring would decrease.

Answer: (C)

10. A block is hanging from a spring, which causes the spring to be stretched by 0.2 meter. If a more massive block were attached to the spring instead, what would be different?

(A) There would be no change in the stretch of the spring.
(B) The stretch of the spring would increase.
(C) The stretch of the spring would decrease.

Answer: (B)

11. A shot is launched into the air with a certain speed. If a more massive shot were used but with the same speed, compare the kinetic energies of the shots.

(A) The kinetic energies of the two shots would be the same.
(B) The kinetic energy of the more massive shot would be greater.
(C) The kinetic energy of the more massive shot would be less.

Answer: (B)

12. A shot is launched into the air with a certain speed. A second shot with twice the mass of the original is launched with twice the speed. Compare the kinetic energies of the shots.

(A) The kinetic energies of the two shots would be the same.
(B) The kinetic energy of the more massive shot would be greater by a factor of 2.
(C) The kinetic energy of the more massive shot would be greater by a factor of 4.
(D) The kinetic energy of the more massive shot would be greater by a factor of 8.
(E) The kinetic energy of the more massive shot would be less by a factor of 2.
(F) The kinetic energy of the more massive shot would be less by a factor of 4.

Answer: (D)

13. We examine two poles used for pole vaulting. One has a flex number of 15 (centimeters) and the other has a flex number of 20. Which pole will bend more during a competition?

(A) The pole with the flex number of 15.
(B) The pole with the flex number of 20.

Answer: (B)

14. A can of Pepsi "One" contains ~1 Food calorie. How many scientific calories is that?

(A) 1 calorie
(B) 10 calories
(C) 100 calories
(D) 1000 calories
(E) 10,000 calories

Answer: (D)

15. A strong man lifts an Atlas Stone from the ground to a height of 1 meter. A second strong man lifts an Atlas Stone of the same mass to a height of two meters. Compare the work done in each case:

(A) The work done the two strong men is the same.
(B) The second strong man does twice as much work as the first one.
(C) The second strong man does one half as much work as the first one.

Answer: (B)

16. A strong man lifts an Atlas Stone from the ground to a height of 1 meter. A second strong man lifts an Atlas Stone with half the mass to a height of two meters. Compare the work done in each case:

(A) The work done the two strong men is the same.
(B) The second strong man does twice as much work as the first one.
(C) The second strong man does one half as much work as the first one.

Answer: (A)

17. In a World's Strongest Man competition, one strong man pulls a pallet, doing 500 Joules of work in a time of 30 seconds. A second strong man pulls the same pallet, doing 1000 Joules of work in a time of 60 seconds Compare the power in each case:

(A) The power exerted by the two strong men is the same.
(B) The second strong man exerts twice as much power as the first one.
(C) The second strong man exerts one half as much power as the first one.

Answer: (A)

18. Compare the work done lifting a bowling ball to a certain height at sea level vs. in Denver, the "Mile High City".

(A) The work done is the same.
(B) The work done is greater at sea level.
(C) The work done is greater in Denver.

Answer: (B)

19. Rank the amount of Food calories burned per hour for the following sports:

A Hockey
B Cross country skiing
C Aerobics
D Bowling

Answer: B > A > C > D

20. In the pole vault competition, why do you want the pole to be as light as possible? (Because the vaulter has to run with it.)

21. Why is good padding more important in current pole vaulting competitions as opposed to those held many years ago (e.g. foam vs. sand pit)?

22. In addition to the sports discussed in the chapter, can you think of other sports in which elastic energy is stored and released?

23. You are riding a bicycle at constant speed along a horizontal road. You stopped pedaling and the bicycle comes to rest. Is energy conserved? Explain.

24. The unit "Joule" is shorthand for the combination $kg \cdot (m/s)^2$. Explain the origin of this unit.

25. In the calculation of the change in gravitational potential energy of the pole vaulter, we ignored the mass of the pole. What is wrong with this approximation?
(For one thing, the change in the height of the pole is not included.)

26. Besides curling, name some sports in which there is work done by friction.
(shuffleboard, skiing, snowboarding, bobsledding, bowling)

## Exercises

1. A Hershey's "Kiss" contains ~22 Food calories. How many scientific calories is that?

__________ calories

Answer: 22,000 calories

2. Which requires more work?

(A) raising a 0.4 kilogram ball a distance of 20 meters
(B) raising a 2 kilogram ball a distance of 3 meters

Answer: (A)

3. It takes 60 Newtons to compress a spring by 20 centimeters. How much total force would be required to compress the spring by a total of 10 centimeters?

___________ Newtons

Answer: 30 Newtons

4. A ball of mass 0.5 kilogram is thrown with a speed of 4 meters per second. If a ball of mass 1 kilogram is thrown with the same initial speed, how will the kinetic energy be affected?

(A) The kinetic energy will remain the same.
(B) The kinetic energy will double.
(C) The kinetic energy will quadruple.
(D) The kinetic energy will be 1/2 the original value.
(E) None of the above.

Answer: (B)

5. A ball of mass 1 kilogram is thrown with a speed of 4 meters per second. If the speed is increased to 8 meters per second with the same mass, how will the kinetic energy be affected?

(A) The kinetic energy will remain the same.
(B) The kinetic energy will double.
(C) The kinetic energy will quadruple.
(D) The kinetic energy will be 1/2 the original value.
(E) None of the above.

Answer: (C)

6. A ball of mass 1 kg is thrown with a speed of 6 meters per second. If the speed and mass are both doubled with the same mass, how will the kinetic energy be affected?

(A) The kinetic energy will remain the same.
(B) The kinetic energy will double.
(C) The kinetic energy will quadruple.
(D) The kinetic energy will be 1/2 the original value.
(E) None of the above.

Answer: (E)

7. A bowling ball of mass 5 kilograms is thrown with a speed of 4 meters per second. What is the kinetic energy of the ball?

___________ Joules

Answer: 40 Joules

8. A pole vaulter with total mass including pole of 80 kilograms approaches the bar with a speed of 8 meters per second. What is the kinetic energy of the vaulter plus pole?

___________ Joules

Answer: 2560 Joules

9. A pole vaulter with a mass of 80 kilograms approaches the bar with a kinetic energy of 2400 Joules. If all this kinetic energy is converted into gravitational potential energy, what is the maximum (change in) height of the vaulter?

___________ meters

Answer: 3 meters

10. A pole vaulter has a mass of 70 kilograms and carries a pole with mass of 10 kilograms. She approaches the bar with a speed of 6 meters per second. If instead she carried a pole with mass 20 kilograms, what would her speed have to be to have the same total kinetic energy (vaulter plus pole) during the approach?

___________ meters per second

Answer: 5.66 meters per second

11. Approximately how many hours would Michael Phelps have to swim to burn off his targeted daily calorie consumption of 12,000 food calories?

(A) 5 hours
(B) 7 hours
(C) 10 hours
(D) 15 hours
(E) 17 hours
(F) 20 hours

Answer: (E)

12. A spring with spring constant k = 100 N/m is stretched by 0.2 meter. What is the force exerted by the stretched spring?

___________ Newtons

Answer: 20 Newtons

13. A spring with spring constant k = 100 N/m is stretched by 0.2 meter. How much elastic energy is stored in the stretched spring?

___________ Joules

Answer: 2 Joules

14. With a force of 300 Newtons A spring is stretched by 0.3 meter. Find the spring constant of the spring.

___________ Newtons per meter

Answer: 1000 Newtons per meter

15. A spring stretched by 0.3 meter has stored energy of 90 Joules. Find the spring constant of the spring.

___________ Newtons per meter

Answer: 2000 Newtons per meter

16. A spring has a stretched length of L and has stored energy of 100 Joules. By how much would the stretch of the spring have to increase to store energy of 144 Joules?

___________ x L

Answer: 0.2 x L

17. Find the work done in raising an Atlas Stone of mass 100 kilograms a distance of 2 meters?

___________ Joules

Answer: 2000 Joules

18. You eat a Big Mac. How many hours would you have to play shuffleboard to burn off the calories you obtained?

___________ hours

Answer: 3.3 hours

19. For the men's slalom event at the 2010 Winter Olympics in Vancouver, won by Giuliano Razzoli of Italy, the vertical drop was 200 meters. Assuming Razzoli had a mass of 90 kilograms, find the change in gravitational potential energy during his run.

___________ Joules

Answer: 180,000 Joules

20. For the women's Super G event at the 2010 Winter Olympics in Vancouver, won by Andrea Fischbacher of Austria, the vertical drop was 600 meters. Assuming the change in gravitational potential energy during her run was 360,000 Joules, find her mass.

___________ kilograms

Answer: 60 kilograms

21. For the women's Super G event at the 2010 Winter Olympics in Vancouver, won by Andrea Fischbacher of Austria, the vertical drop was 600 meters. Assuming the change in gravitational potential energy during her run was 360,000 Joules and that her final speed was 40 meters per second, find her kinetic energy at the bottom of the run.

___________ Joules

Answer: 48,000 Joules

22. For the women's Super G event at the 2010 Winter Olympics in Vancouver, won by Andrea Fischbacher of Austria, the vertical drop was 600 meters. Assuming the change in gravitational potential energy during her run was 360,000 Joules and that her final speed was 40 meters per second, find the energy during the run that went into friction and air resistance.

___________ Joules

Answer: 312,000 Joules

23. You drop a bowling ball (weight of 20 pounds) from a cliff with height of 50 meters.

a. What is the kinetic energy of the ball just before you release it?

___________ Joules

b. What is the potential energy of the ball just before you release it?

___________ Joules

c. What is the kinetic energy of the ball just before it hits the ground (ignore air resistance)?

___________ Joules

d. What is the speed of the ball just before it hits the ground (ignore air resistance)?

___________ meters per second

Answers:
a. 0
b. 4450 Joules
c. 4450 Joules
d. 31.6 meters per second

24. You throw a bowling ball (weight of 20 pounds) with an initial speed of 15 meters per second straight down from a cliff with a height of 50 meters.

a. What is the kinetic energy of the ball just before you release it?

___________ Joules

b. What is the potential energy of the ball just before you release it?

___________ Joules

c. What is the kinetic energy of the ball just before it hits the ground (ignore air resistance)?

___________ Joules

d. What is the speed of the ball just before it hits the ground (ignore air resistance)?

___________ meters per second

Answers: a. 1000
b. 4450 Joules
c. 5450 Joules
d. 35 meters per second

25. A Hostess Twinkie (before the company went out of business) had a food calorie content of 150 Calories. Assuming all the energy expended went into using up these calories, how long would you have to play shuffleboard to use up the calories from one Twinkie?

___________ minutes

Answer: 42.7 minutes

26. A Milky Way Bar has a food calorie content of 270 Calories. How many Joules is that?

___________ Joules

Answer: 1,129,680 Joules

27. A Milky Way Bar has a food calorie content of 270 Calories. Assuming all the energy expended went into using up these calories, how many stairs would you have to climb to use up the calories from one Milky Way Bar? Assume a stair height of 0.2 meter and take your mass to be 60 kilograms.

___________ stairs

Answer: 9414 stairs

28. A Strong Man lifts a 120 kilogram Atlas Stone a height of 2 meters in a time of 5 seconds. How much power did the athlete generate?

___________ Watts

Answer: 480 Watts

29. A football player pushes a training sled which has a weight of 1200 Newtons with a constant force of 600 Newtons. The sled does not move under this force. How much work did the athlete do?

___________ Joules

Answer: 0 Joules

30. A football player pushes a training sled which has a weight of 1000 Newtons with a constant force of 500 Newtons. After pushing for 30 seconds, the sled still has not moved under this force. How much power did the athlete generate?

___________ Watts

Answer: 0 Watts

31. A football player pushes a training sled which has a weight of 1200 Newtons with a constant force of 600 Newtons. After pushing for 30 seconds, the sled has moved 5 meters at constant speed.
a. What is the work done by the athlete?

___________Joules

b. What is the work done by friction?

___________ Joules

Answers: a. 3000 Joules
b. 3000 Joules

32. A football player pushes a training sled which has a weight of 1200 Newtons with a constant force of 600 Newtons. After pushing for 30 seconds, the sled has moved 5 meters at constant speed. How much power did the athlete generate?

___________ Watts

Answer: 100 Watts

33. The lowest point in the continental U.S. is 86 meters (282 feet) below sea level at Badwater, California. The highest point in the continental U.S. is 4,421 meters (14,405 feet) above sea level on the top of Mt. Whitney in California. Assuming that these places were next to each other (they are actually only ~85 miles apart), for a 60 kilogram hiker,

a. What would be the change in potential energy climbing from Badwater to the top of Mt. Whitney?

___________ Joules

b. If the hike took 2 days, what would be the average power output?

___________Watts

Answers: a. $2.70 \times 10^6$ Joules
b. 15.6 Watts

34. The highest point in the world is 8,848 meters (29,029 feet) above sea level on the top of Mt. Everest. For a 75 kilogram hiker,

a. What would be the change in potential energy climbing from sea level to the top of Mt. Everest?

___________ Joules

b. If the hiker then jumped from the top of Mt. Everest, what would his speed be just before he hit the ground (assuming that he would hit the ground at sea level and that we can ignore air resistance - both bad assumptions!)

___________ mph

Answers: a. $6.64 \times 10^6$ Joules
b. 925 mph

35. A horse is turning a mill wheel, pulling with a force of 180 pounds. To turn the wheel, the horse makes a circuit around the wheel 2.4 times every minute, covering a distance of 76.5 feet in each circuit.

a. What is the work done by the horse in one circuit?

___________ Joules

b. What is the average power exerted by the horse?

___________ Watts

c. What is the average power exerted by the horse in horsepower (using the conversion that 1 horsepower = 747 Watts)?

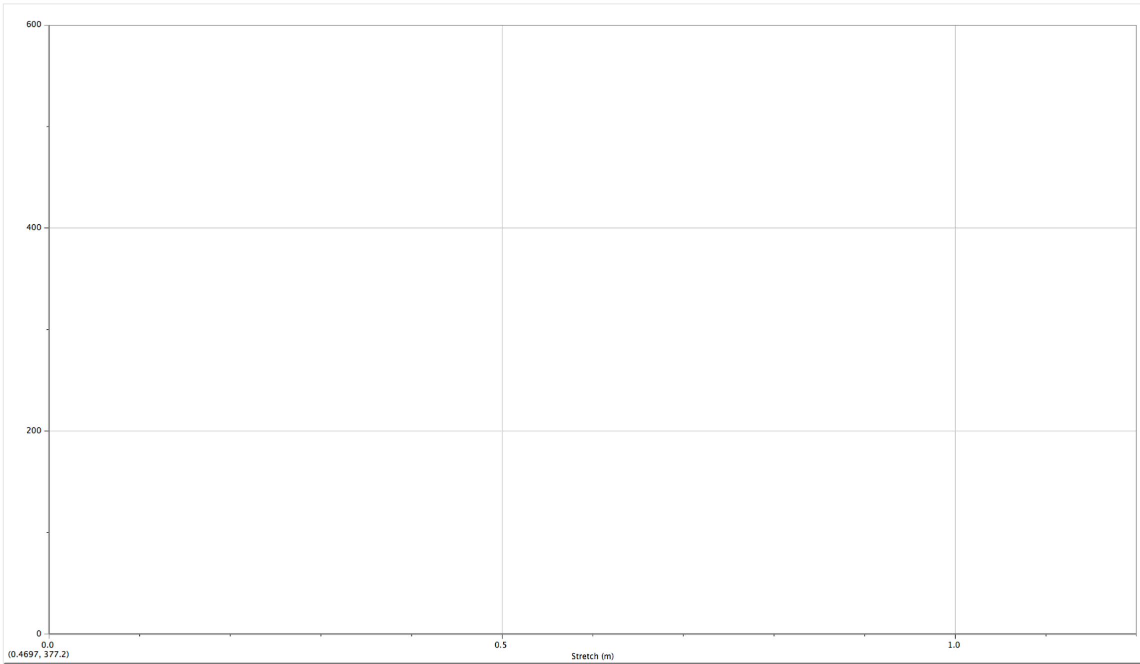
___________ horsepower

Answers: a. 18,676 Joules
b. 747 Watts
c. 1.0 horsepower

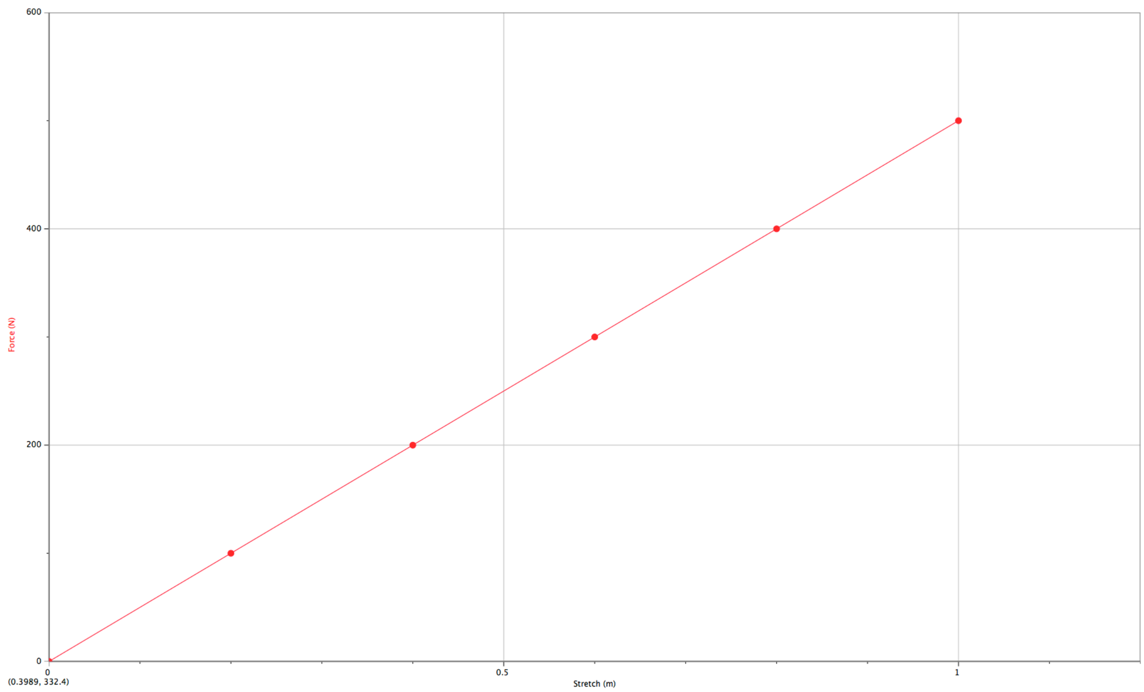
36. The data below depicts the stretch of a spring vs. applied force.
a. Plot the data with force on the vertical axis and stretch on the horizontal axis.

| Stretch (m) | Force (N) |
|---|---|
| 0 | 0 |
| 0.2 | 100 |
| 0.4 | 200 |
| 0.6 | 300 |
| 0.8 | 400 |
| 1.0 | 500 |

a.




Answer:




b. From the graph, find the spring constant of the spring, which will be given by the slope of the plot.

___________ Newtons per meter

<u>Answer</u>: 500 Newtons per meter

37. Rank the kinetic energies of these sports projectiles:

A Pelota throw in jai alai (mass 0.125 kg; speed 150 mph)
B Softball fast pitch (mass 0.185 kg; speed 37 mph)
C Soccer kick (mass 0.45 kg; speed 90 mph)
D Pitched fastball (mass 0.145 kg; speed 100 mph)
E Tennis serve (mass 0.058 kg; speed 120 mph)

<u>Answer</u>: C > A > D > E > B

# CHAPTER 6: Impulse and Momentum

A martial arts concrete-breaking demonstration

http://discovermagazine.com/~/media/import/images/4/5/d/karate.jpg

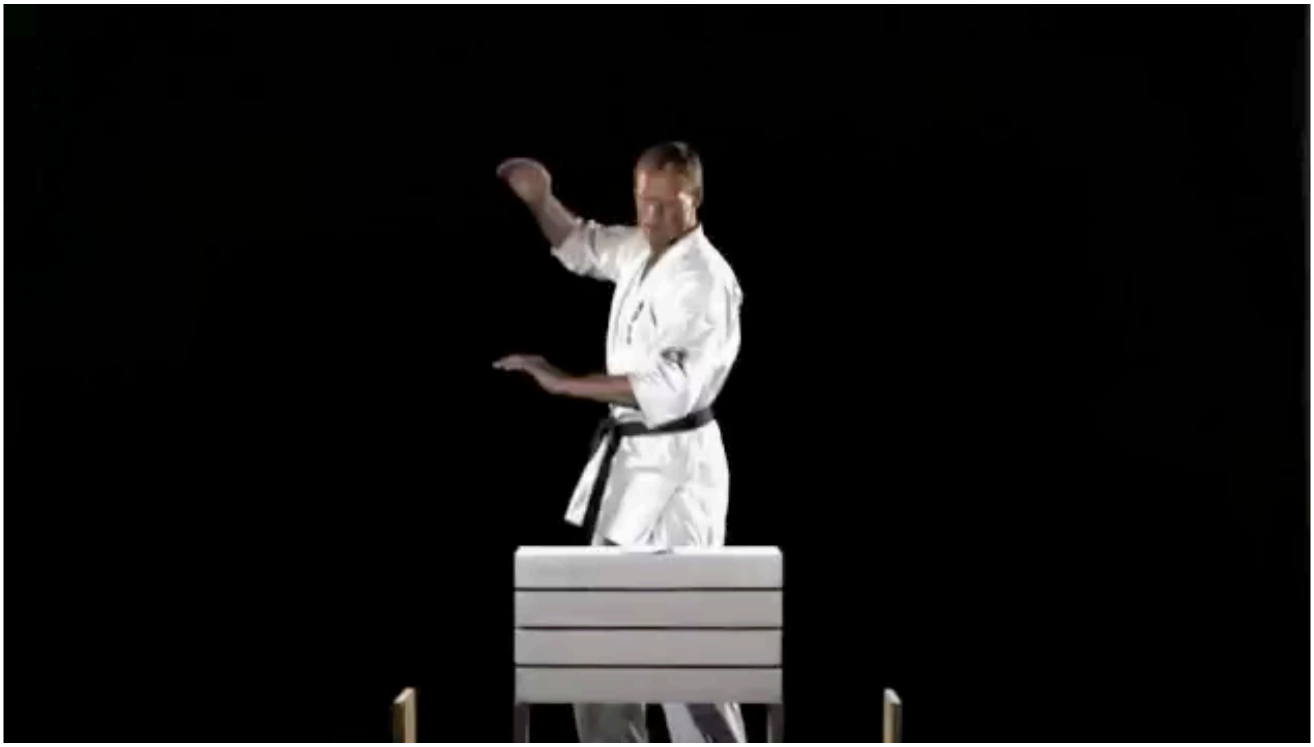
Now select and watch VIDEO 6.1.

VIDEO 6.1: A demonstration of concrete-breaking using martial arts

https://digitalcommons.uri.edu/physicsofsports/25/

## 6.1: Impulse and Momentum

In the video opening this chapter you watched a martial arts concrete breaking demonstration. Were you impressed? Wow! is all I can say. Is there any physics behind this? Yes, is the answer that you should expect by now. Now let's watch another version of this feat. Select VIDEO 6.2 and watch Sensei Frank Mikkelsen of Randers Karate School break four concrete blocks in slow motion.



VIDEO 6.2: Sensei Frank Mikkelsen demonstrates concrete-breaking using martial arts.

https://digitalcommons.uri.edu/physicsofsports/26/

Do you think you could break a concrete block? I couldn't. How is it possible? It takes ~2000 Newtons of force to break a concrete block with a thickness of 1.5 inches. Let's think about how much force that is.

QUIZ 6.1

Approximately how many kilograms would have a weight of 2000 Newtons?

( ) 10 kilograms
( ) 20 kilograms
( ) 50 kilograms
( ) 100 kilograms
( x ) 200 kilograms
( ) 400 kilograms
( ) 1000 kilograms

200 kilograms is a lot of mass, weighing in at ~450 pounds. For example, could you push or press with a force that great? I don't think I could. Let's find out how much force I can push with.

Now I'm going to push a force plate against a wall "with all my might!"

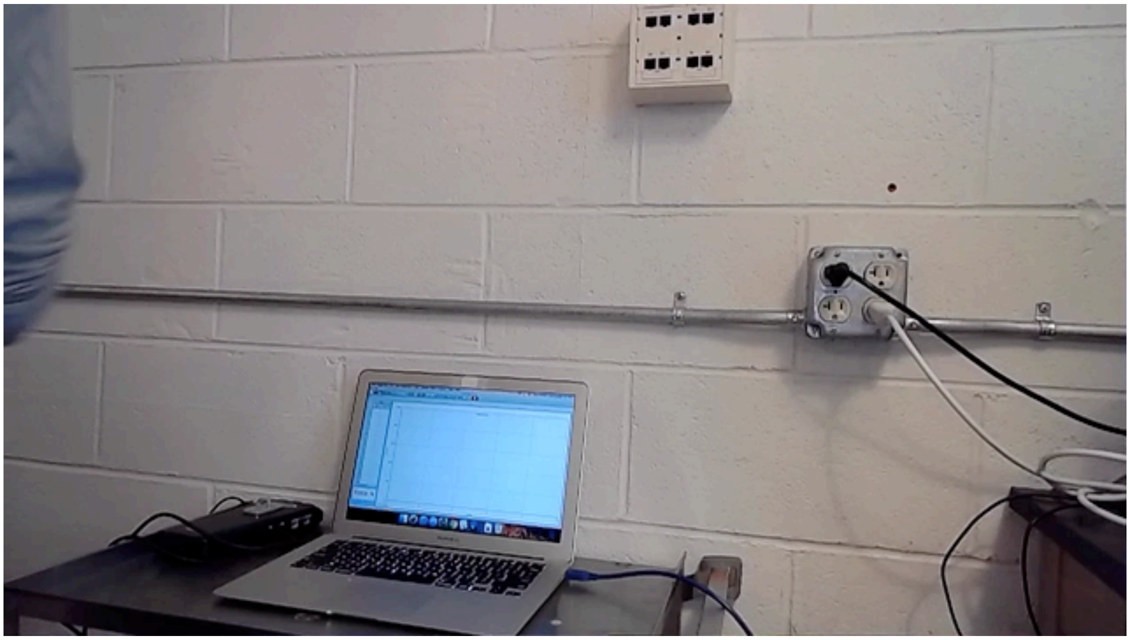
Before I do that, take a guess as to how much force I can push with.

QUIZ 6.2

Guess in what range of force I can push a force plate:

( ) 0-500 Newtons
( ) 500-1000 Newtons
( ) 1000-1500 Newtons
( ) 1500-2000 Newtons
( ) 2000-2500 Newtons
( ) >2500 Newtons

Now select VIDEO 6.3 and see what happens.



VIDEO 6.3: Pushing on a Force Plate

https://digitalcommons.uri.edu/physicsofsports/27/

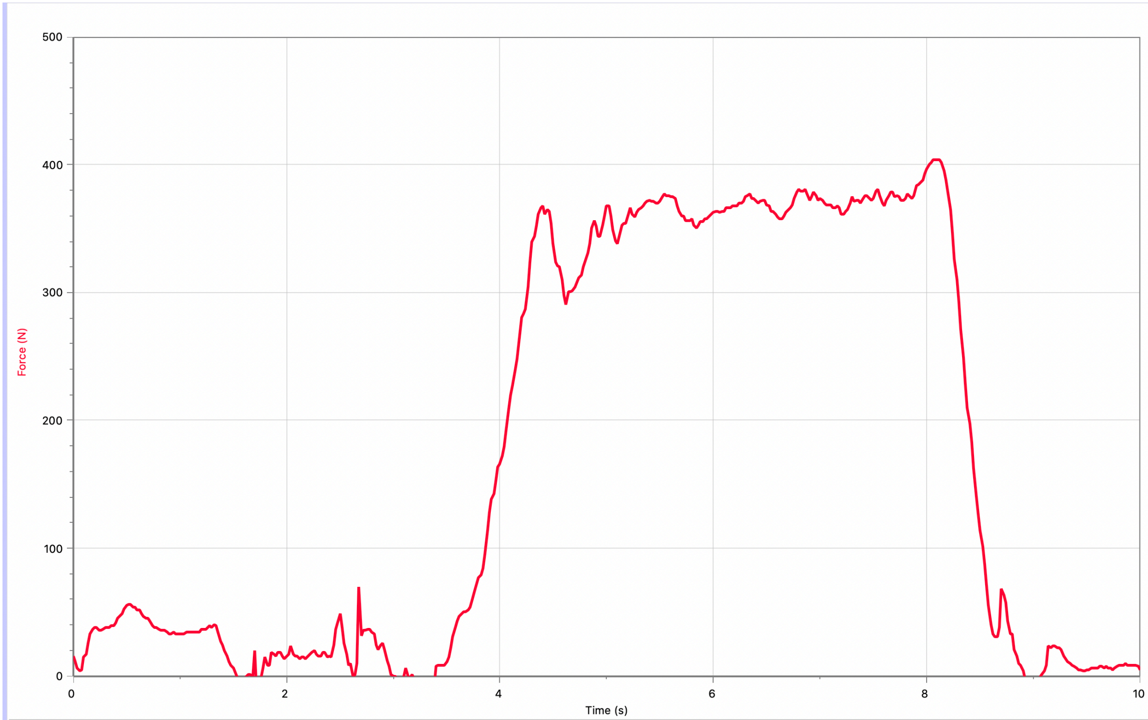



FIGURE 6.1: Pushing on a Force Plate

The result of my pushing effort is shown in Figure 6.1. O.k, I got up to ~400 Newtons Not that impressive and well short of the ~2000 Newtons needed to break a concrete slab. My guess is that if you stacked 45 ten-pound weights (that's ~2000 Newtons) on a supported concrete slab, that the slab would not break even then. It's important in these martial arts feats that the force of the blow (from the side of hand, fist, elbow, foot) be concentrated in a relatively small area of the slab. But that's still not enough. How does the martial arts master achieve this force since I don't think he could push a whole lot harder than me, certainly not 5 times harder!

Let's think about the videos. The hand or fist comes in very "fast" which means it has a relatively high speed and velocity. What if the sensei could increase his speed? Would that be more effective in breaking a concrete slab or not?

## QUIZ 6.3

Would greater hand or fist speed be more effective in breaking concrete?

( x ) More effective
( ) No difference
( ) Less effective

Of course, the answer is that the greater hand speed would be more effective in breaking a concrete slab. Instead, what if the sensei had a more massive hand hitting the block at the same speed (I guess he could be holding a lead weight or something). Would that matter? I hope it is clear that a greater striking mass would also be more effective in breaking the concrete.

So we have speed and mass both being significant. And, in fact, this combination is a very important one in physics. The product of mass times speed (really velocity) is called **momentum**. Our everyday version of "momentum" might include these examples: a defensive end has a lot of momentum before he hits the quarterback; a team had a lot of momentum going into the playoffs; and you had a lot of momentum going into the final exam for a course. The first example uses momentum in the physics sense; the last two - not physics.

Momentum is generally given the symbol, "p" (not to be confused with power, and is given by this equation (in the simple case - I'll elaborate later):

$$p = mv \qquad \text{Equation 6.1}$$

The unit of momentum is nothing special, just the combination (kilogram)x(meter per second) or $kg \cdot m/s$.

QUIZ 6.4

A curling stone with a mass of 20 kilograms is sliding on the ice with a speed of 3 meters/second. What is the momentum of the stone?

________________ $kg \cdot m/s$

(Answer: 60 $kg \cdot m/s$)

We've established that the mass and speed of the hand or fist are both important in breaking concrete (or wood, etc.) in martial arts feats, but that still hasn't gotten us to the force - enough force to break a concrete slab (~2000 Newtons). The connection is through the physics concept of **impulse** coupled with the **impulse-momentum theorem**. Impulse, I, is given by

$$I = Ft \qquad \text{Equation 6.2}$$

where F is the force applied during an impulse and t is the time duration of the impulse. The units again are just the simple combination of Newton times second or $N \cdot s$.

The impulse-momentum theorem relates the impulse to the momentum change:

where $\Delta p$ is the change in momentum (specifically the initial momentum subtracted from the final momentum). $\Delta$, pronounced "delta", is the Greek symbol that stands for "change" in physics nomenclature - final minus initial of whatever. (Unit-wise, we can see from Equation 6.2 that the units of N·s must be equivalent to kg·m/s.)

So now we can put it all together and relate the force to other factors. If we rearrange Equation 6.2 we can solve for the force:

$$F = \frac{\Delta p}{t} = \frac{\Delta(mv)}{t} = \frac{m\Delta v}{t} \qquad \text{Equation 6.3}$$

Now it's time to put in some numbers and see if this makes sense. Specifically, can a martial arts sensei generate a striking force >2000 Newtons *over a short time interval* in order to break that concrete slab? Does physics work? (Yes!)

According to an earlier study using time elapsed photography, a martial arts black belt can strike with a hand speed of ~14 meters per second (31 mph). The mass of the hand was ~ .68 kilograms (weight of ~1.5 pounds). The time of the strike was found to be approximately 4 one thousandths of a second (0.004 s = 4 milliseconds). We'll assume that the hand comes to rest after the strike (not a bad assumption based on the slow motion VIDEO 6.2 ) so the change in speed will be equal to the initial speed before contact. Let's substitute these numbers into Equation 6.3 to find the force of the strike:

$$F = \frac{m\Delta v}{t} = \frac{(0.68\,\text{kg})(14\,\text{m/s})}{0.004\,\text{s}} = 2380\,\text{N}$$

So it did work. Though the sensei could not push on a concrete block with the necessary breaking force of ~2000 Newtons, he can generate that much force for a very short period of time. By the way, according to the research I looked at, a martial arts novice can generate a hand speed of ~6 m/s. Everything else being equal in the previous calculation (doubtful actually - what else is probably different ?) this would generate a force of ~1000 Newtons, probably enough to break a board but not a concrete slab. Don't try it!

QUIZ 6.5

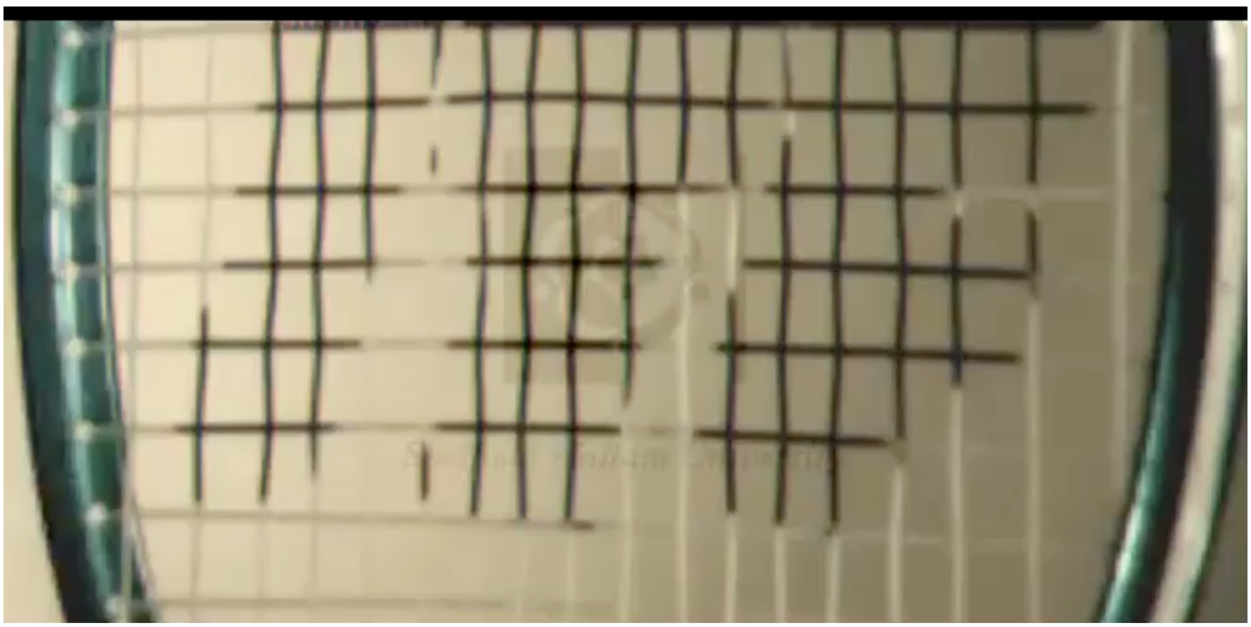
A very soft ball hits a wall with a force of 8 Newtons. The time of the impulse is 1/4 second (0.25 s). What is the impulse generated by the ball on the wall?

________________ N·s

(Answer: 2 N·s)

## 6.2: Impulse 2

From the impulse-momentum theorem, whenever there is a process such as a collision that involves a change in momentum (usually due to a change in velocity), then that process involves an impulse which is equal to the force times the duration of the process (we'll just say "collision" for "process" for now). This force is technically the average force as we generally expect that the force will not be constant throughout the collision (as for example in Figure 6.1). If you think about it, there are many, many examples of collisions in sports involving athlete-on-athlete, ball-on-athlete, ball-on-bat, -racket, -foot, etc. All of these collisions take some time to occur though it is not always obvious when you see one in real time. Select VIDEOS 6.4 and 6.5 and you will watch two such collisions in slow motion.



VIDEO 6.4: Tennis ball hitting a tennis racket

https://digitalcommons.uri.edu/physicsofsports/28/


VIDEO 6.5: Golf ball being struck by a golf club

https://digitalcommons.uri.edu/physicsofsports/29/

Are you surprised to see how much a golf ball is compressed during its collision with a golf club? In slow motion you can clearly see that both tennis ball-on-racket and golf ball-on-club take some time to occur, though that time is quite short. Since the golf ball started from rest, the change in momentum of the ball is just the momentum (mass times velocity) of the ball after it leaves the club. (More about the change in momentum of the tennis ball later.)

Did you notice the compression of the tennis and golf balls during the collisions (I hope so!) and the very obvious stretch of the strings in the tennis racket. These are all examples of the temporary storing of a kind of energy that we learned about in the last chapter. Which kind?

QUIZ 6.6

What form of energy is stored in the stretched tennis racket strings and compressed golf and tennis balls in the previous videos?

( ) Kinetic Energy
( ) Gravitational Potential Energy
( x ) Elastic Potential Energy

Those changes are similar to the bending of the pole vault pole during the swing up, though that process takes considerably longer than the tennis and golf collisions.

Now we're going to consider an oddball example of the impulse-momentum theorem - the egg drop. I'm going to drop an egg onto a tile floor from a height of 1 meter. What's going to happen when the egg hits the floor? Splat! of course. Before I do that, what kind of energy is stored in the egg at a height of 1 meter before I release it?

QUIZ 6.7

What form of energy is stored in the egg at a height of 1 meter before I release it?

( ) Kinetic Energy
( x ) Gravitational Potential Energy
( ) Elastic Potential Energy

Next, I'll drop the egg onto a fluffy pillow. What will happen?

QUIZ 6.8

What will happen to the egg landing on a pillow?

( ) Egg breaks
( x ) Egg doesn't break

O.k. select VIDEOS 6.6 and 6.7 to see what happens.

VIDEO 6.6: Egg drop on tile floor

https://digitalcommons.uri.edu/physicsofsports/30/

VIDEO 6.7: Egg drop on pillow

https://digitalcommons.uri.edu/physicsofsports/31/

Is it what you expected? Just before the egg hit the floor or the pillow, the previously stored gravitational potential energy had converted into what form of energy? I hope "kinetic energy" popped into your head, So the egg had pretty much the same speed (~6 meters per second) and therefore the same momentum just before each collision. After the collision, the eggs were at rest (in one form or another) so their momenta were zero. Keeping the impulse-momentum theorem in mind, why did the egg-on-tile break but not the egg-on-pillow?

## QUIZ 6.9

What is the physics behind the egg-on-pillow surviving intact?

( ) The momentum change of the egg-on-pillow was smaller than for the egg-on-concrete.

( ) The velocity of the egg-on-pillow was smaller than for the egg-on-concrete.

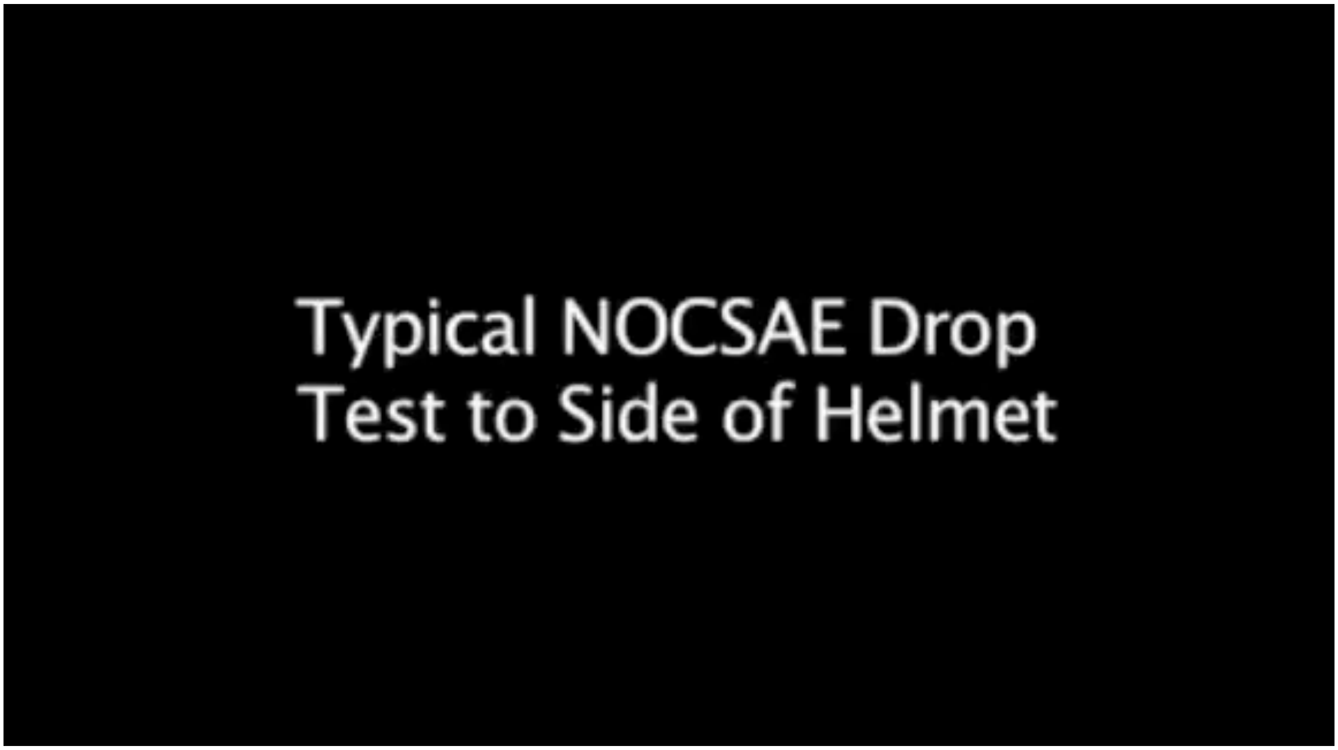
( ) The time of the collision of the egg-on-pillow was less so the force was less.

( x ) The time of the collision of the egg-on-pillow was greater so the force was less.

When the egg lands on the pillow, the pillow compresses, increasing the time of the collision and the time of the impulse. From Equation 6.3, longer time means less force so the egg does not break.

What does breaking or not breaking an egg have to do with sports? Actually, many physics departments sponsor "egg-drop" contests, so it is a kind of sport. But more importantly, reducing the force by increasing the collision time is very important with many examples I can think of in sports applications as well as in the everyday world. In sports, think of padding worn by hockey and football players (and others), knee and elbow pads worn by volleyball players and skaters, helmets in many sports, the padding the athlete falls into after a high jump or pole vault, boxing gloves, and the list goes on. (Can you think of other examples?). All are designed to reduce F by increasing t.

You may have heard of the recent concern about concussions among especially football players, both adults and children. Obviously the first line of defense against these is the helmet the football player wears. The football helmet has been put under a lot of scrutiny lately - how good is it in preventing concussions, how long can it be worn before it should be replaced, etc. Clearly helmet testing is very important. Select VIDEO 6.8 and watch a typical helmet test by the NOCSAE, the National Operating Committee on Standards for Athletic Equipment.

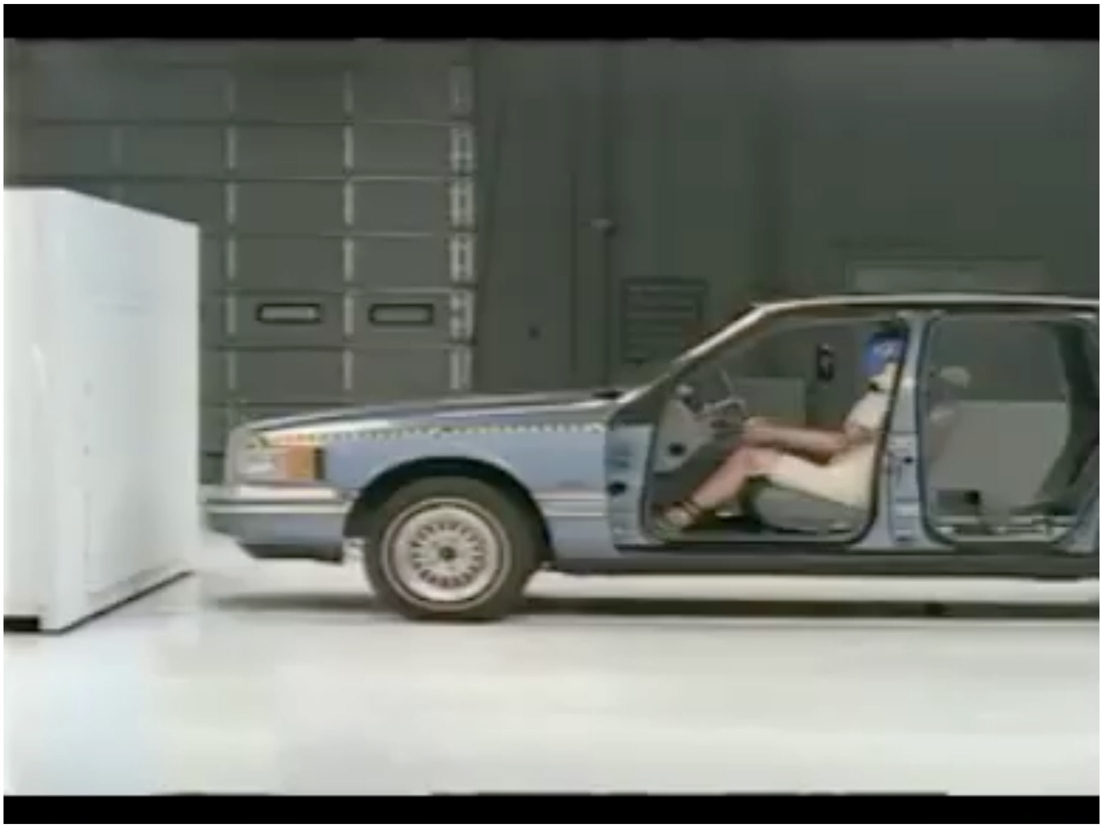



VIDEO 6.8: Helmet test

https://digitalcommons.uri.edu/physicsofsports/32/

I hope you've got down the concept and importance of impulse in sports!

I want to close this section with one very important, life-saving example of impulse and momentum, a valuable safety feature that is available in most modern automobiles. Can you guess what I am talking about? Select VIDEO 6.9 and find out.



VIDEO 6.9: Automobile crash test

https://digitalcommons.uri.edu/physicsofsports/33/

Yes, I want to have an air bag in my car. How about you?

## 6.3: Momentum Conservation


FIGURE 6.2: Tennis racket-ball collision

http://ffden-2.phys.uaf.edu/webproj/211_fall_2014/Max_Hesser-Knoll/max_hesserknoll/Images/TennisBallRacquetImpact.jpg

Let's consider the golf and tennis videos again. As we discussed earlier, the golf ball starts from rest so its change in momentum is equal to the momentum of the ball just after colliding with the club. The tennis ball, on the other hand is initially moving towards the racket. After the collision it is moving away from the racket. To find the change in momentum we need to know the momentum before the collision and add that to the momentum after the collision.

From a physics point of view this comes about because momentum is a vector as are force, velocity, and acceleration. Momentum must be a vector since p = mv and velocity is a vector (mass is a scalar - just a number). Therefore, momentum can be positive or negative depending on the direction and we can also discuss the amount (component) of momentum in orthogonal directions such as parallel and perpendicular to the ground as was the case for two-dimensional motion in Chapter 2 and forces in Chapters 3 and 4. (Similarly, impulse is also a vector.)

Back to the tennis video again. The racket hits the ball with a certain average force and time, the impulse causing the momentum of the tennis ball to change. But what if a physical process occurs in which there is no force, or at least no external force such as racket hitting ball? If F = 0 in Equation 6.2, then $\Delta p = 0$ also. What does that tell you about the momentum before such a process occurs as compared to the momentum after the process?

QUIZ 6.10

If F = $\Delta$p = 0, what does that tell you about the momentum before a process as compared to the momentum after the process?

( ) The momentum before the process is less than the momentum after the process.
( ) The momentum before the process is greater than the momentum after the process.
( x ) The momentum before the process is the same as the momentum after the process.

If the change in a physical quantity (such as momentum) during an event or process is zero, that means that this quantity is "conserved", it is the same before and after the event. We learned about Conservation of Energy in the previous chapter. **Conservation of Momentum** is also a very important law in physics. Energy we learned is always conserved. Momentum is conserved when the (total) external force is zero. This is often true or approximately true during many physical processes such as collisions during the short time interval in which they occur. Eventually (usually quite soon after a collision) the momentum of an object will change as external forces such as gravity, friction, etc. become significant.

As an equation we can write Conservation of Momentum as:

$$p_i = p_f \quad \text{or} \quad m_i v_i = m_f v_f \qquad \text{Equation 6.4}$$

where "i" and "f" indicate the initial and final values before and after a collision or some other interaction that conserves momentum. Note that if several objects are involved, we need to add up their momenta to find the initial and final totals.

Let's consider conservation of momentum in a couple of examples of collisions. First, we'll watch Nick Palmieri of the New Jersey Devils collide with Mike Weber of the Buffalo Sabres in a hockey game. Choose what you think will happen.

QUIZ 6.11

Weber is not skating particularly fast before the collision. Palmieri skates into Weber and almost stops after banging into him. To conserve momentum, what must happen to Weber after the collision?

( ) Weber must stop also.
( ) Weber must skate into Palmieri.
( x ) Weber must travel in the direction that Palmieri was skating before the collision.

Select VIDEO 6.10 and find out if you are correct.

VIDEO 6.10: Hockey collision between Nick Palmieri and Mike Weber

https://digitalcommons.uri.edu/physicsofsports/34/

Hopefully you selected the correct answer. Most of the momentum from Palmieri is transferred to Weber during the collision.

Another example: let's look a second time at a collision during a football game that we first saw in Chapter 3. Click on VIDEO 6.11 and watch again a pretty violent collision between Ryan Clark and Willis McGahee.


VIDEO 6.11: Football collision between Ryan Clark and Willis McGahee

https://digitalcommons.uri.edu/physicsofsports/35/

We can treat this pretty much as a one-dimensional collision. At the beginning of the video, Clark and McGahee are running more or less directly at each other. After the collision, both players are on the ground and almost "at rest" (in the physics sense anyway - they probable didn't feel like they were at rest!). So how was momentum conserved here?

To understand conservation of momentum in this situation we need to remember that momentum is a vector so it can be negative or positive. Before the collision, the two players are running towards each other with similar momenta *in magnitude* (I would estimate that their speeds and masses are similar) but in <u>opposite</u> directions; therefore, their momenta almost cancel and the <u>total</u> momentum of the system of Clark-McGahee is close to zero just before the collision. After the collision they have stopped moving so the total momentum is clearly zero then as well. Once again, momentum conservation and physics works! I'm sure if you search around you can find many more examples of collisions in sports. In many sports, it's part of the game.

## 6.4: Momentum Conservation 2

The football collision of Clark and McGahee was a good approximation of a one-dimensional collision. They were more or less running directly towards each other before they collided and then stopped after the collision. To understand momentum conservation in this case we needed to make use of the fact that momentum is a vector which has both magnitude and direction.

One of the values of treating momentum (or force, velocity, etc.) as a vector is that we can separate vectors into components in different directions and analyze them separately. This is something we would want to do in the case of a collision that occurs in two dimensions rather than one. Now select VIDEO 6.12 and watch Jeanette Lee, the "Black Widow", demonstrate an excellent example of two-dimensional collisions.

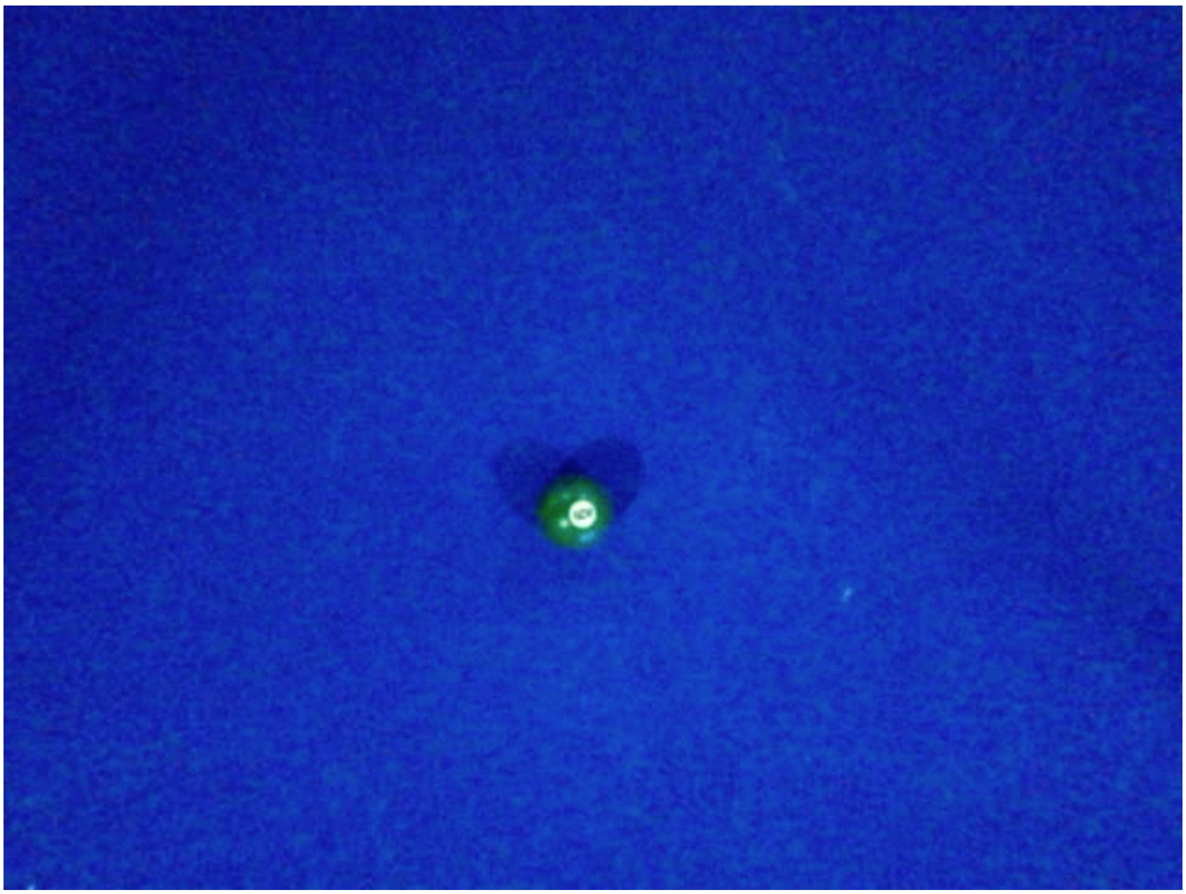
VIDEO 6.12: Billiards shot by Jeannette Lee

https://digitalcommons.uri.edu/physicsofsports/36/

Billiards provides great sports examples of momentum conservation in two-dimensional collisions. (Curling is another good example - though the curling example we considered in Chapter 1 did not involve a collision.) The billiards video we just saw would be a little difficult to analyze in detail. We'll examine a more manageable one instead.

Now we're going to analyze a video of a simple collision between two billiard balls. Before the collision, one ball is at rest so its initial momentum is clearly 0. The white cue ball enters the picture and strikes the stationary green five ball. After the collision the balls fly off in different directions, with a mix of velocities and momenta.

Select VIDEO 6.13 and watch the video.



VIDEO 6.13: Collision between two pool balls

https://digitalcommons.uri.edu/physicsofsports/37/

## QUIZ 6.12

We'll call the initial direction of the white cue ball the y-direction and the perpendicular direction the x-direction. What is the total momentum in the x-direction before the collision?

( x ) The momentum in the x-direction is zero before the collision.
(   ) The momentum in the x-direction is greater than zero before the collision.

Since neither ball is moving in the x-direction before the collision, the total momentum in the x-direction before the collision is clearly equal to zero. Since momentum is conserved, the total x-momentum should also be zero after the collision (we'll find out). What about the momentum in the y-direction?

Now we'll analyze the video and check to see if momentum really is conserved in both directions in this example. I'll map out the positions of both balls frame-by-frame. Let's take a look at my analysis of this billiards collision, presented below (FIGUREs 6.3 and 6.4). First look at the x- and y-positions of the 5 ball vs. time. The position does not change for a while. Of course, that is right since it doesn't move until it is struck by the cue ball. After the collision, both the x- and y-positions of the ball change, as they should.

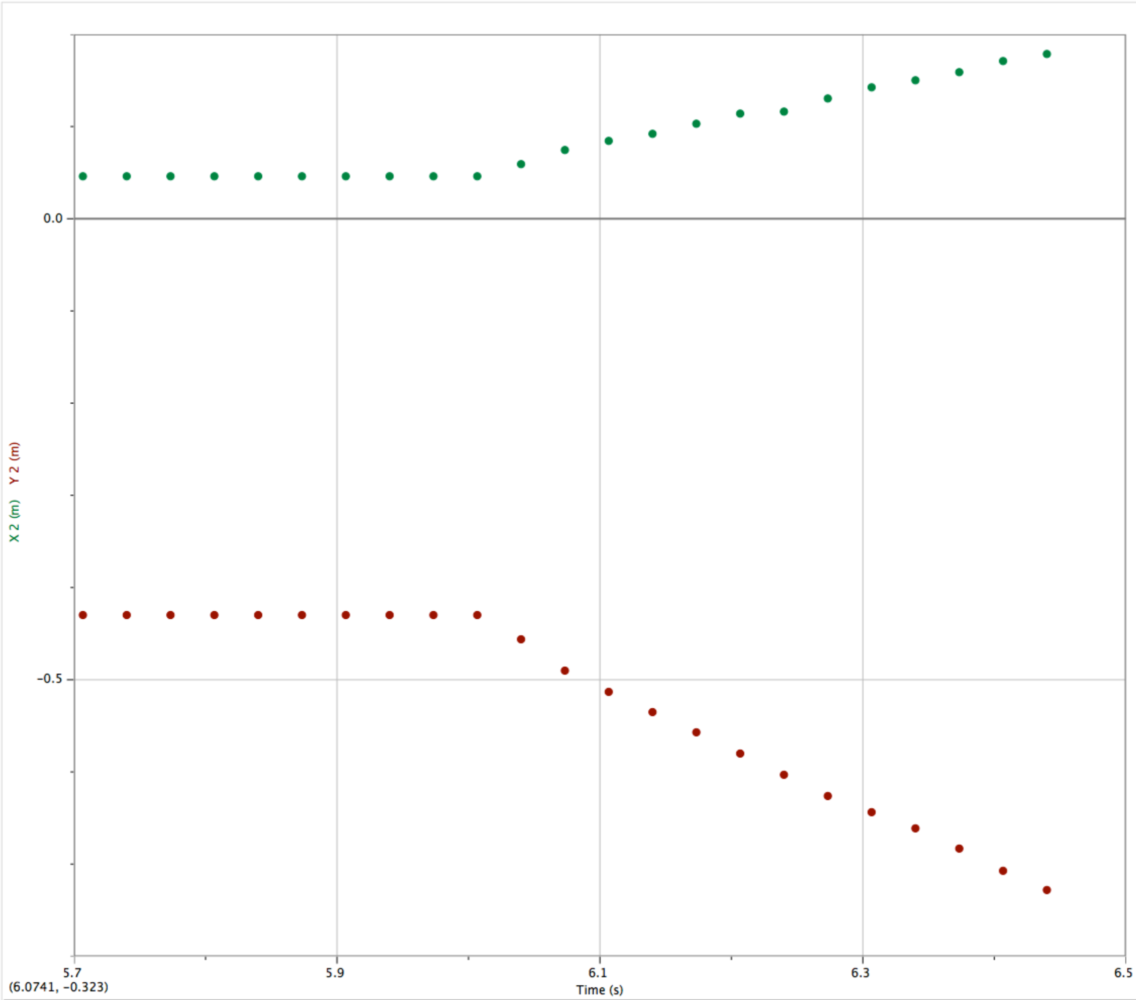



FIGURE 6.3: Digitization of the five ball

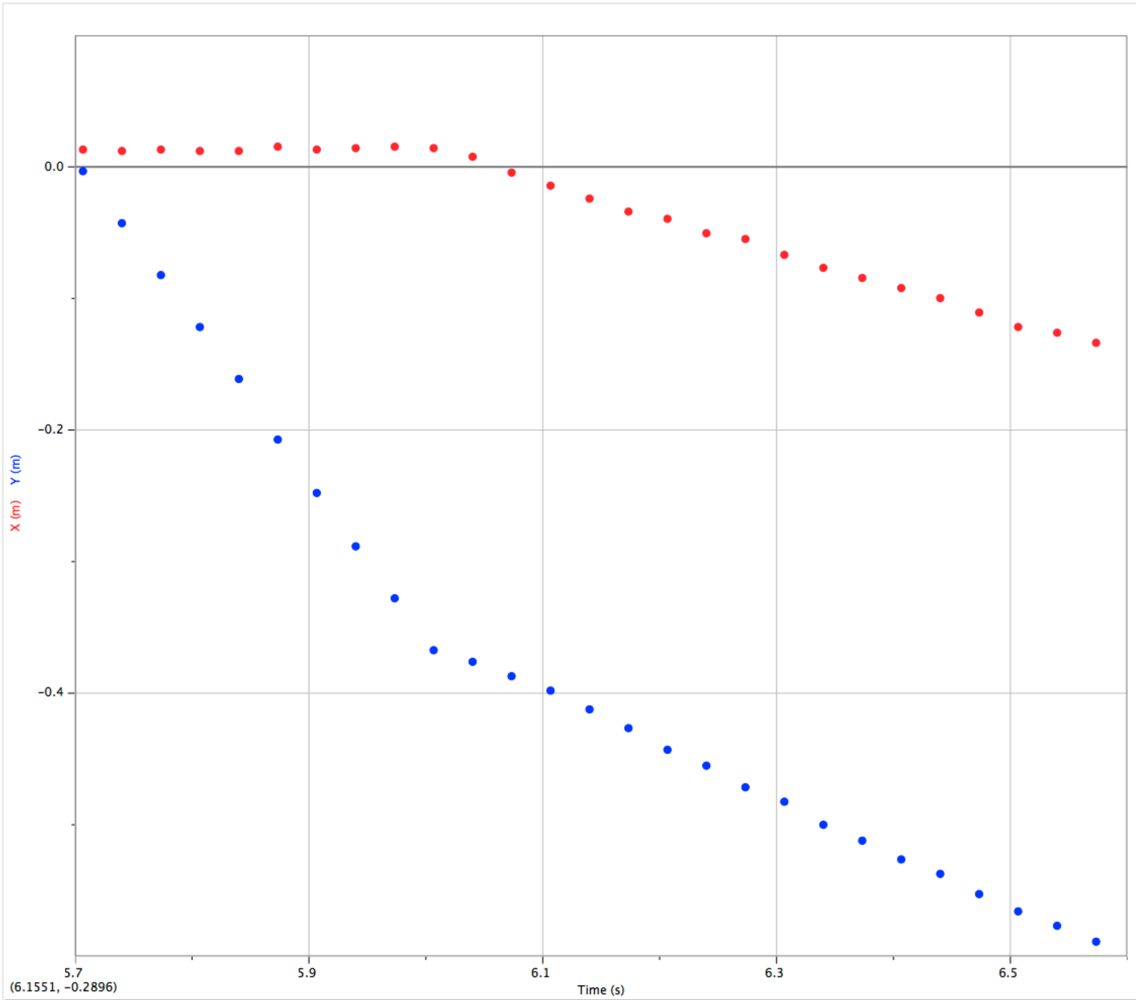



FIGURE 6.4: Digitization of the cue ball

What about the cue ball? It's x-position remains constant at first as it should since initially it is traveling only in the y-direction. After the collision, the ball heads off in the x-direction opposite from the green ball. This is necessary to conserve momentum - the momenta of the two balls must cancel at all times in the x-direction. The cue ball continues changing its y-position in the same direction as it started out. I do notice that the spacing between y points is less after the collision as compared with before. Does this make sense? Yes - the velocity of the cue ball is reduced after the collision as some of the y-momentum is transferred to the five ball, so the velocity of the cue ball must decrease.

Now I'll have the computer plot the total momentum in both directions from this analysis (FIGURE 6.5).

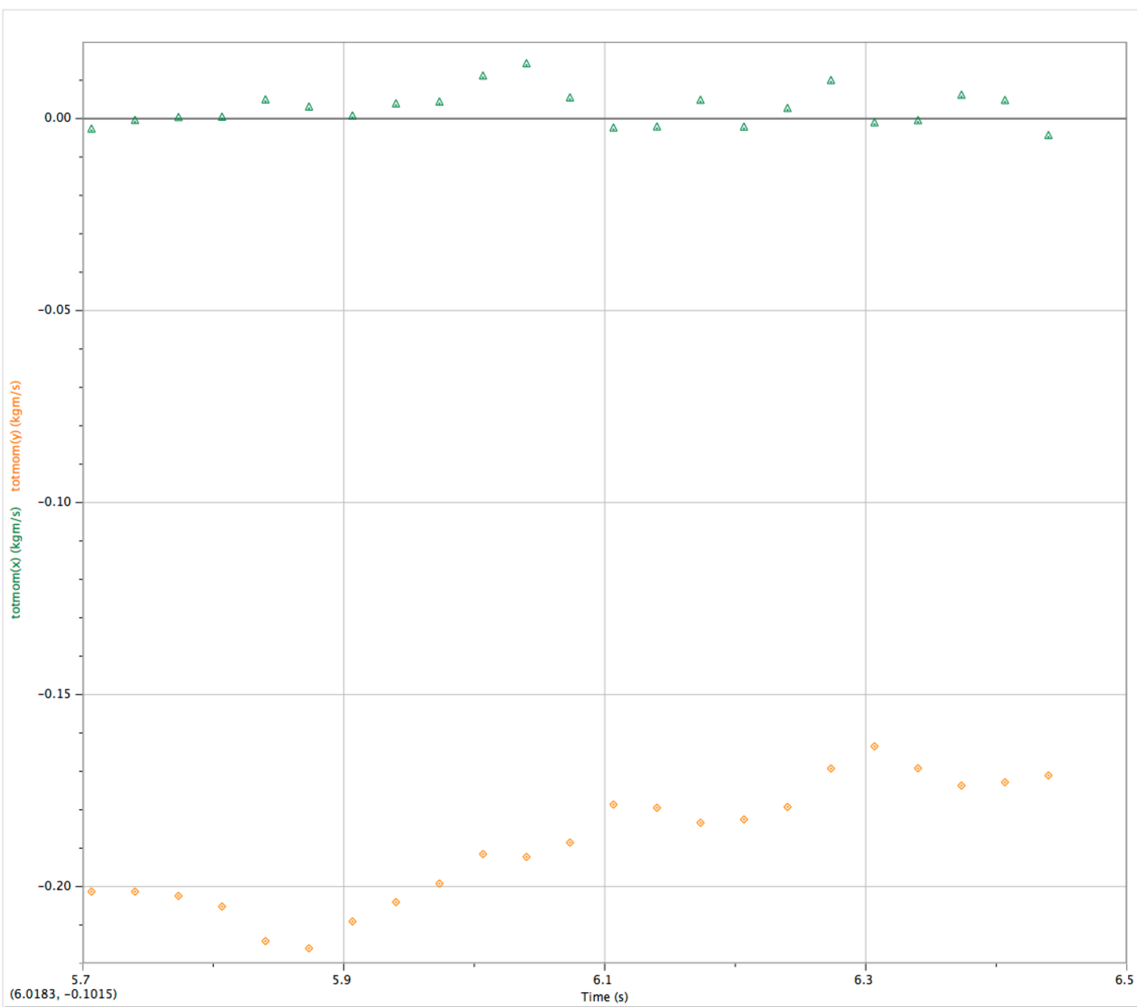


FIGURE 6.5: Plot of the total momentum of the billiard balls in the x- and y-directions

Let's consider this plot. The momentum in the x-direction starts at zero and remains zero as it should. These results make sense and momentum in that direction is clearly conserved (equal to approximately 0 for all times plotted). The momentum in the y-direction starts at a value of ~$0.2\,\mathrm{kg \cdot m/s}$ which should correspond to the momentum of the moving cue ball before the collision. The momentum in this direction does change a little as time goes on. Not exactly a proof of momentum conservation in this case but maybe close enough for this demo. Well, I hope you get the idea!

A few more words about collisions. We've already discussed the fact that as long as the collision times in sports or elsewhere are short enough that external forces do not play a role, then the total momentum of the system is conserved before and after the collision.

What about energy? Well, according to what we learned in Chapter 5, energy is <u>always conserved</u> in any process, though there could be many forms of energy you might have to consider to make it balance in this example.

All of our examples of collisions involve the motion of one or more objects (there wouldn't be much of a collision if no objects were moving!). So what about the energy of motion in particular? Is kinetic energy conserved during a collision? The answer is "No" at least in any realistic situations. In some collisions such as billiards or curling, the kinetic energy is close to being conserved. In others, such as the football collision we watched, the kinetic is clearly not conserved (after all the football players were both moving before the collision but almost “at rest” after it).

When the kinetic energy is conserved in a collision, in physics we call this an **elastic collision**. When the kinetic energy is not conserved in a collision (which realistically is almost all of the time in the real world), we call this an **inelastic collision**. The collision of two billiard balls is about as close to an elastic collision as you can get in sports examples. One consequence of this near-elastic collision is that the balls move away from each after the collision with an angle very close to 90$^{\circ}$ between them. Take another look at the video and check it out; and remember this the next time you are playing pool!

## 6.5: Coefficient of Restitution

In this section we are going to consider some simple collisions - ball on something. That "something" could be a racket or floor or court surface or wall, etc. We'll start with a demo. I'm going to drop a golf ball from a height of 1 meter onto a tile floor. What will happen?

QUIZ 6.13

I drop a golf ball onto a tile floor from a height of 1 meter. What happens?

( ) The golf ball will bounce back up to a height of 1 meter.
( x ) The golf ball will bounce back up to a height less than 1 meter.
( ) The golf ball will bounce back up to a height greater than 1 meter.

I hope you selected less than 1 meter as the final height of the golf ball after the bounce. If the golf ball bounces higher than 1 meter then this would violate conservation of energy. Its initial energy is all gravitational potential energy corresponding to a height of 1 meter. That's all the energy the golf ball has. It would need more than that to get to a greater height. To reach a height of exactly 1 meter would require that the collision of ball on tile is perfectly elastic. We've already discussed the fact that virtually all collisions in the real world are inelastic, though some can come close to being elastic. Therefore, a 1 meter bounce is also essentially impossible.

Now that we've got that out of the way, how high do you think the golf ball will bounce? Pick a range and then we'll check.

QUIZ 6.14

I drop a golf ball onto a tile floor from a height of 1 meter. How high will it bounce?

( ) 0-0.25 meter
( ) 0.25-0.5 meter
( ) 0.5-0.75 meter
( ) 0.75-1.0 meter

Now select VIDEO 6.14 and we'll find out. Make a note of the bounce height. We'll need that number later.

VIDEO 6.14: Golf ball dropped from a height of 1 meter onto a tile floor. Note that in the video the heights of 1.0 m, 0.75 m, 0.5 m, and 0.25 m are indicated by horizontal lines.

https://digitalcommons.uri.edu/physicsofsports/38/

Did you guess the height range correctly? I got a bounce height of 0.8 meter. Was that close to your estimate?

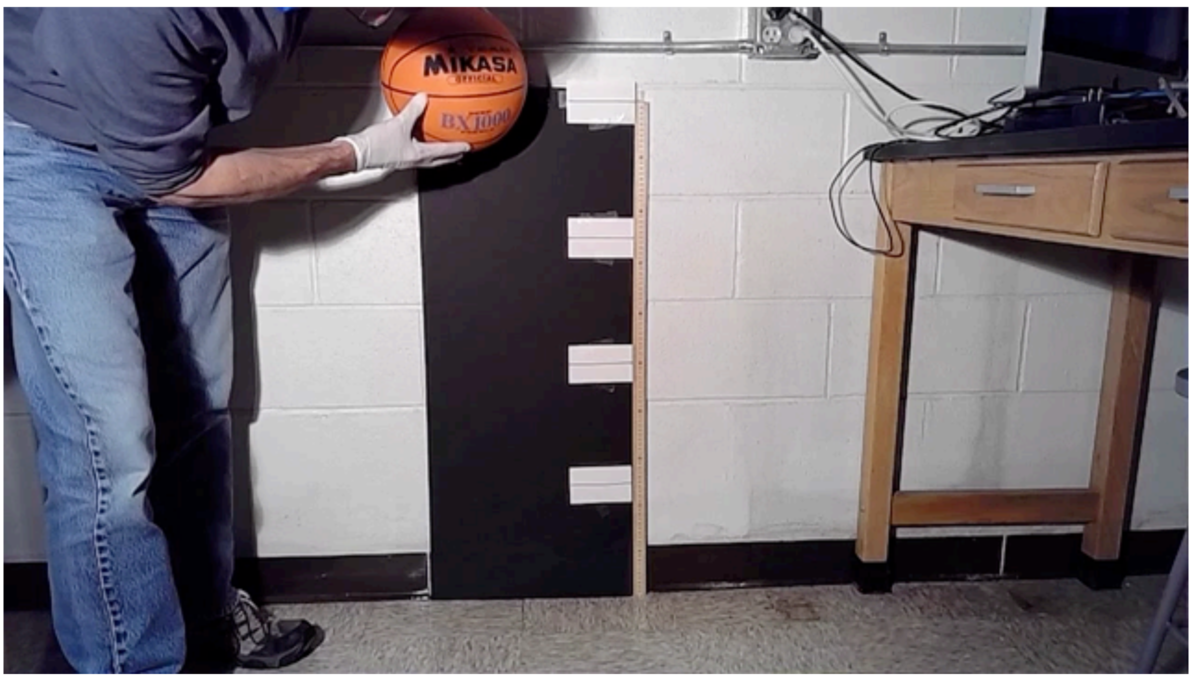
Let's look at another type of ball, a basketball in this case. Do you think the bounce height will be different?

QUIZ 6.15

I drop a basketball onto a tile floor from a height of 1 meter. What happens?

( ) The basketball will bounce to the same height as the golf ball.
( ) The basketball will bounce to a greater height than the golf ball.
( x ) The basketball will bounce to a lesser height than the golf ball.
.

Now select VIDEO 6.15 and we'll find out.  Make a note below of the height the ball reaches.




VIDEO 6.15: Basketball dropped from a height of 1 meter onto a tile floor

https://digitalcommons.uri.edu/physicsofsports/39/

QUIZ 6.15

Basketball bounce height = ____________ meter

I got a bounce height for this ball of ~0.7 meter. Was that close to yours? So the golf ball bounced a little higher than a basketball. Is that what you guessed?

The "bounciness" of a ball is characterized by a number called the **Coefficient of Restitution** (COR). The number would be 1 (no units) for a perfectly elastic collision and between 0 and 1 for any realistic ball-surface collision. A COR of 0 means the ball or object stops once it hits the surface (like the egg drop on the tile floor!). The higher the number, the more "bouncy" is the combination. I've listed a few balls below. Try to rank them by their COR's (assume the same surfaces).

QUIZ 6.16

Rank the Coefficients of Restitution for the following balls:

A Baseball
B Superball
C Tennis Ball
D Basketball
E Soccer Ball

Answer: B > D > C > A

How did you do?

COR's are often written on the ball itself. Why are they this important? If you think about it, in sports the bounciness of balls (the COR's) had better be very uniform from ball to ball. Imagine a batter hitting a very bouncy baseball vs. one that is not bouncy. Not good. With an identical swing one could be a home run, the other a fly ball out. Clearly the balls in all sports must be carefully tested and regulated by various agencies. Below I've provided a table of COR"s for a number of sports balls. Any surprises?

| **Sport Ball** | **COR** |
|---|---|
| Superball | 0.76 |
| Golf Ball | 0.78 |
| Tennis Ball on Racket | 0.85 |
| Ping Pong Ball | 0.94 |

| | | |
|---|---|---|
| Basketball on wood floor | 0.75 | 0.81-0.85-linoleum |

How is the Coefficient of Restitution measured? By bouncing objects as we did and measuring the height? Not quite. The COR is actually defined as the ratio of the speed of a ball just after a collision with a surface divided by the speed just before the collision. However, using some simple kinematics, we can use the bounce height to get the COR. Without going into detail, the COR is the square root of the height ratio. For the golf ball we dropped on the tile floor, a bounce height of 0.8 m corresponds to a COR of 0.89 which is fairly close to the standard golf ball COR in the table above. For the basketball, I compute a COR from my measurements of 0.84, again relatively close.

You should imagine that not just the ball (and other conditions we'll discuss momentarily) but also the surface the ball collides with will affect the "bounciness", the COR. For example, most competitive basketball games are played on wooden floors, so the measurement we did would be more relevant if we had bounced the basketball off a wooden floor instead of a tile floor. In fact, the given COR for a basketball on a linoleum floor is ~0.81-0.85, right in the range of my measurement.

What else might affect the bouncing performance of a ball? Any suggestions? Temperature? Age of the ball? Pressure of the ball (for inflated balls anyway.) Anything else?

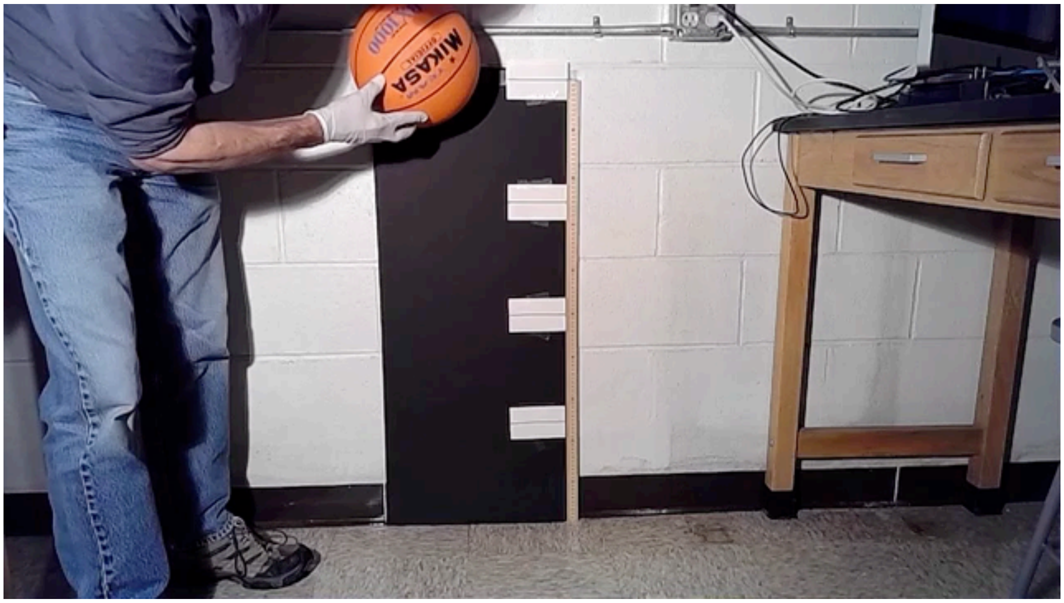
What if we let some of the air out of a basketball? What would happen?

QUIZ 6.17

If we let some air out of a basketball, how would the bounce height be affected?

( x ) The bounce height of the basketball would decrease.
( ) The bounce height of the basketball would remain the same.
( ) The bounce height of the basketball would increase.

Let's find out. Now select VIDEO 6.16 to watch an under-inflated basketball dropped from a height of 1 meter. (By the way, I had inflated the basketball in VIDEO 6.15 to the regulation pressure of ~8 psi.)




VIDEO 6.16: Under-inflated Basketball dropped from a height of 1 meter

https://digitalcommons.uri.edu/physicsofsports/40/

I got a new bounce height of ~0.4 m (vs. 0.7 m for the properly-inflated basketball in VIDEO 6.15). Makes sense, I hope. How do you think other factors would affect the bounciness of a ball? Does this matter in any case? Maybe you could check it out.

# 6.6: Center of Mass

FIGURE 6.6: High jump by Stefan Holm of Sweden at the 2004 Olympics

https://i.pinimg.com/736x/17/8b/f3/178bf3aaa27f31edb49d9b8a5e51aade--high-jump-olympic-gold-medals.jpg

In the previous chapter, we calculated the gravitational potential energy of pole vaulter Steve Hooker at the top of his vault in his gold-medal winning performance (we came up with ~5100 Joules). To do that calculation we needed his mass, the value of *g*, and his height. But the height of what - his head, his feet, his hands, his waist? We weren't clear but just used the height of the bar that he cleared. But is this correct? Not quite. We really should have used the height of his **center of mass** when he cleared the bar. What is this?

Center of mass is the "average" position of the mass of an object or a collection of objects that are grouped together (often attached). It is usually abbreviated $x_{cm}$ if the object or objects are aligned in one dimension (along the x-axis). For a two- or three-dimensional object we would need to know the average mass position in other directions as well.

Of course in physics we have an equation that gives the center of mass position in one or more dimensions but we don't really need to even know this equation (and I'm not going to write it out!) for you to get the right idea for relatively simple cases. So let's consider some simple cases and we can then use our new understanding to look at some relevant examples in sports.

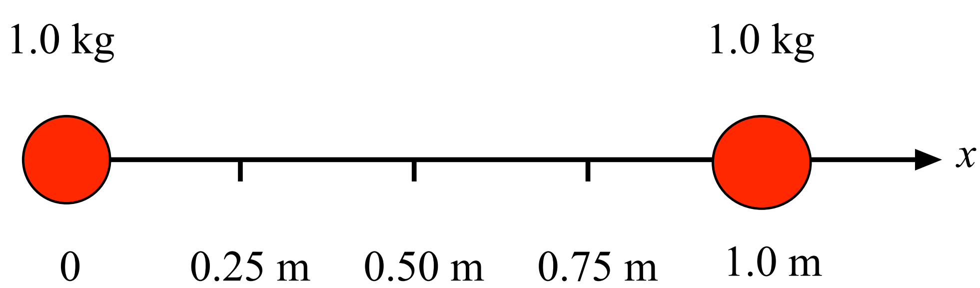



FIGURE 6.7: Schematic of two balls of equal mass placed 1 meter apart

QUIZ 6.18

Two balls of mass one kilogram apiece are connected by a thin rod (sort of like a barbell). We'll assume the mass of the rod is so small we can ignore it. As shown above, the balls are one meter apart at positions of 0 and 1 meter. What is the position of the center of mass of this system? (Remember, think "average position" of the total mass.)

( ) 0
( ) 0.25 meter
( x ) 0.50 meter
( ) 0.75 meter
( ) 1.00 meter

Hopefully you realized that since the balls have equal mass, the center of mass is exactly in the middle.

Let's try again.

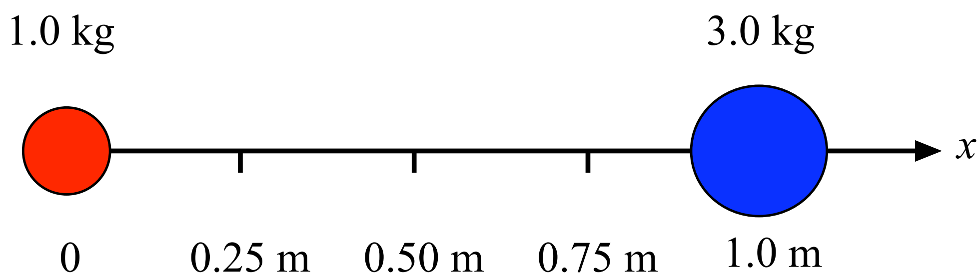



FIGURE 6.78 Schematic of two balls of unequal mass placed 1 meter apart

QUIZ 6.19

Now we've replaced the ball on the right by a more massive, 3 kilogram ball. Everything else is the same. Now, what is the position of the center of mass of this system?

( ) 0
( ) 0.25 meter
( ) 0.50 meter
( x ) 0.75 meter
( ) 1.00 meter

The more massive ball on the right shifted the center of mass in that direction. Clear?

Now let's consider some two-dimensional objects:

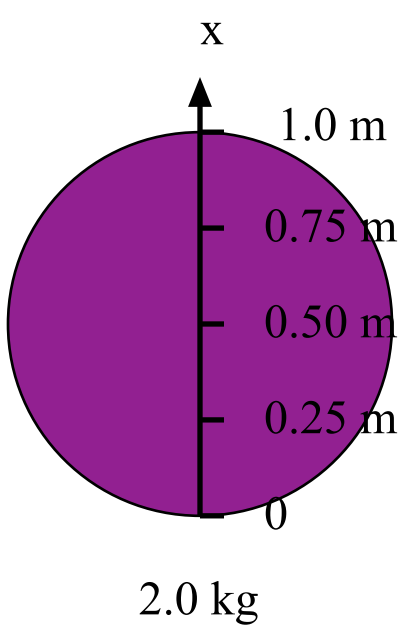



FIGURE 6.9: Schematic of a flat disk

QUIZ 6.20

Above is depicted a (flat) disk with a mass of 2 kilograms and a radius of 0.5 meter. Along the x-direction as shown by the scale, what is the position of the center of mass of the disk?

| | |
|---|---|
| ( ) | 0 |
| ( ) | 0.25 meter |
| ( x ) | 0.50 meter |
| ( ) | 0.75 meter |
| ( ) | 1.00 meter |

Of course, the center of mass is at the center of the disk assuming it is symmetric and uniform. How could the "average" position of the mass be anywhere else? We really already assumed this was the case in the previous two quizzes when we neglected the size of the balls and thought of their masses as being at the centers (we now know that all the mass is not in the center of a ball but the center of mass is).

Another two-dimensional example:

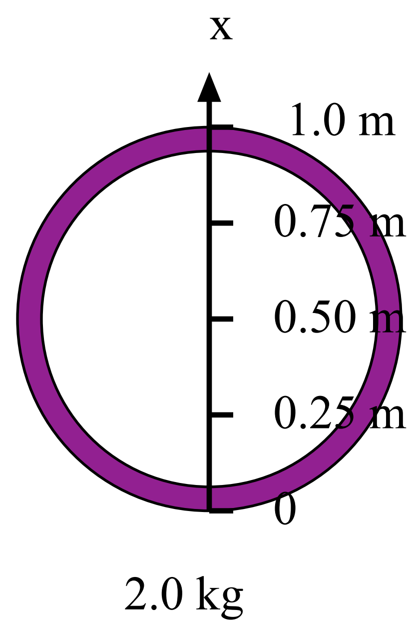



FIGURE 6.10: Schematic of a flat hoop

QUIZ 6.21

Above is depicted a (flat) hoop with a mass of 2 kilograms and a radius of 0.5 meter. Along the x-direction as shown by the scale, what is the position of the center of mass of the disk?

| | |
|---|---|
| ( ) | 0 |
| ( ) | 0.25 meter |
| ( x ) | 0.50 meter |
| ( ) | 0.75 meter |
| ( ) | 1.00 meter |

Again the center of mass is in the center of the hoop in this case. Where else? You can see from this example that the center of mass does not actually have to be in a position where the object has any actual mass.

One more two-dimensional example and then back to sports:

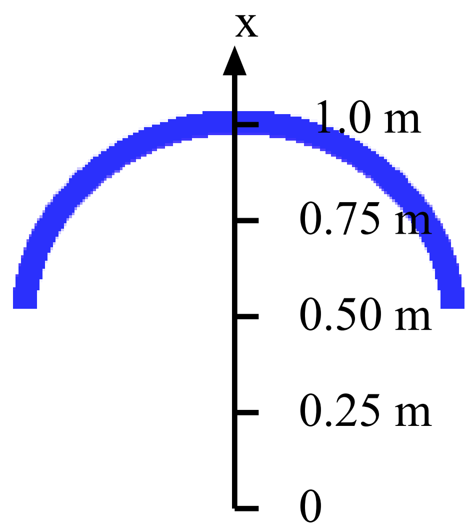



FIGURE 6.11: Schematic of a semicircular hoop

QUIZ 6.22

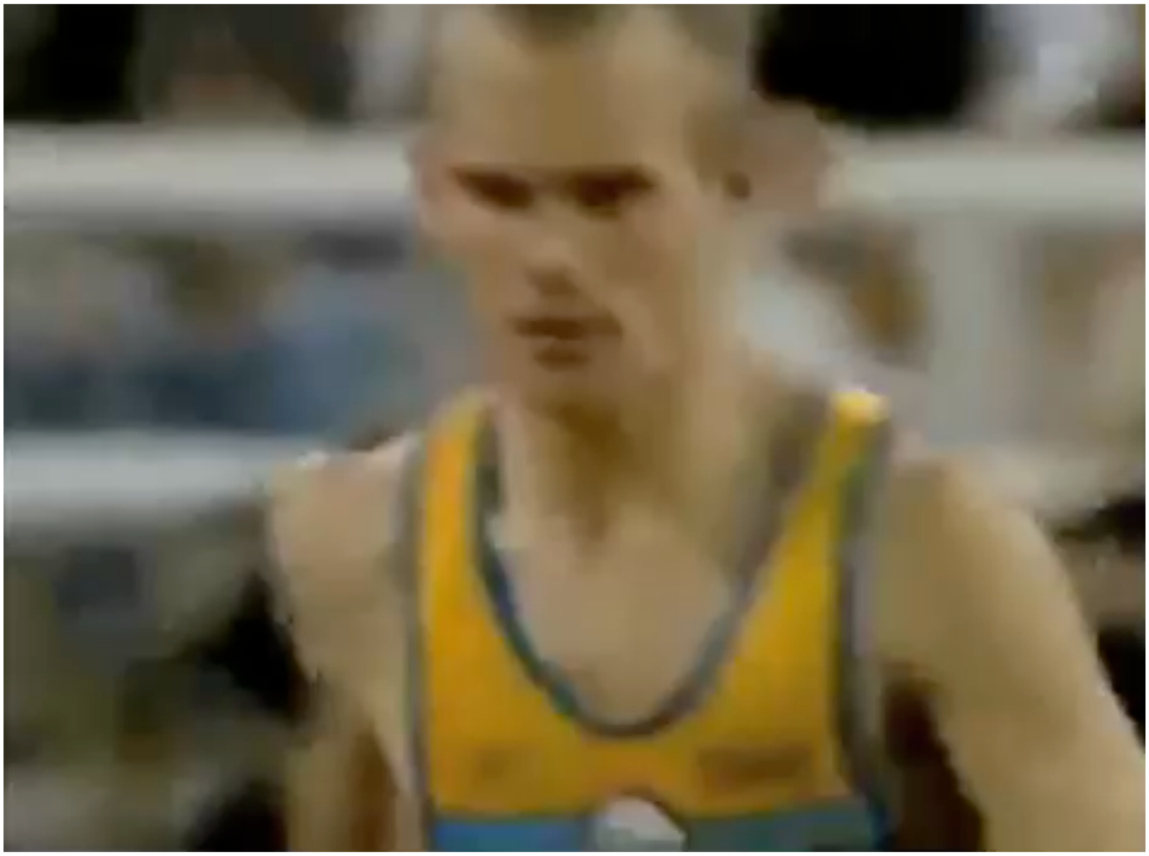
Above is depicted a semicircular hoop with a mass of 2 kilograms and a radius of 0.5 meter. Along the x-direction as shown by the scale, what is the approximate position of the center of mass of the half-hoop?

( ) 0
( ) 0.25 meter
( ) 0.50 meter
( x ) 0.75 meter
( ) 1.00 meter

With this asymmetric shape, the center of mass is pushed up away from the former center of the circle. Whether the center of mass is exactly at 0.75 meter or not would require more detailed information about the shape and a simple calculation, but hopefully you can see 0.75 meter is a good guess and probably close to the correct position.

Now what does this all have to do with sports? As we said at the beginning of the section, it is the position of the center of mass of an extended object, and that object could be an athlete, that determines the gravitational potential energy of the object. The key point is that if you want to know how much energy it takes for an athlete to get over the bar in pole vaulting, for example, you need only know how high the center of mass of the vaulter needs to reach before the vaulter is able to clear the bar.

Confusing? Maybe. What does this mean? Let's look at another good example that illustrates this - the high jump. Select VIDEO 6.17 and watch the gold-medal winning high jump of Stefan Holm from Sweden at the 2004 Summer Olympic Games.



VIDEO 6.17: The gold medal high jump of Stefan Holm of Sweden at the 2004 Olympics

https://digitalcommons.uri.edu/physicsofsports/41/

Can you see the similarity of the shape of Holm's body as he is crossing over the bar (also examine Figure 6.13 at the beginning of this section) to the semicircular hoop we considered in the previous quiz? By curving his body as he crosses the bar, Holm can actually make his center of mass pass nearer to or even under the bar. Since the gravitational energy needed to make this jump only depends on the height of his center of mass, with this high jumping technique Holm needs less total energy to clear the bar by arranging that his center of mass passes under the bar while his body curves over it. Even if the gain is only a fraction of an inch, that could be the difference between winning and losing at the elite level.

This high jump technique is called the "Fosbury flop" after American Dick Fosbury who developed it and used the technique to take the gold medal in the 1968 Olympics. Better padding was partially responsible for this new technique. (Remember better padding means longer collision time, less ????? for the same impulse). Why would better padding be important in implementing this innovative technique? For the pole vault, curling over the bar is also important for the same reason - lower center of mass = less energy needed. (Take another look at Steve Hooker's pole vault in VIDEO 5.1.)

For a person standing straight up or lying down, the center of mass is around waist level. We used this to digitize the running and diving videos in Chapter 1 without further comment. Now we know why that was the correct procedure. Even to digitize the billiards shot in VIDEO 6.13, I marked the pool balls in the center. Well, there's a reason for this - that's where the center of mass is for a homogeneous ball. Can you think of any other sports examples in which the center of mass plays a significant role?

One more center of mass issue. Basketball legend Michael Jordan was often said to defy gravity with his hang time making fantastic shots and dunks and leading to this great billboard for a Nike ad:


FIGURE 6.12: Michael Jordan/Nike Billboard

https://i.pinimg.com/736x/e3/09/22/e309220cba2925243bf0a19567225ac7--jordan--michael-jordan.jpg

Of course, Michael Jordan really didn't defy gravity. He was a great athlete but not great enough to break any laws of physics! But is there any physics in his hangtimes? Yes, of course. In a moment you will watch a video that illustrates one of his performances. Notice what happens to his legs during his shots. Click on the video link below and watch Michael Jordan in action.

VIDEO 6.18: Dunks by Michael Jordan

https://digitalcommons.uri.edu/physicsofsports/42/

Impressive, isn't it!

QUIZ 6.23

When Michael Jordan raises his legs while he is in the air, what happens to the height of his center of mass?

( ) The height of his center of mass stays in the same place.
( x ) The height of his center of mass increases.
( ) The height of his center of mass decreases.

With his legs raised, the height of his center of mass (again, think *average* position of mass) will increase. This has the effect of keeping his body in the air for a slightly longer time - the physics of hang time!

## Chapter 6 Homework

Questions

1. In terms of impulse and momentum, explain briefly why a baseball catcher wears a vest.

(A) The vest reduces the total force if a ball hits his chest.
(B) The vest increases the total force if a ball hits his chest.
(C) The vest increases the collision time between ball and chest, which reduces the maximum force felt by the catcher.
(D) The vest decreases the collision time between ball and chest, which reduces the maximum force felt by the catcher.
(E) Its stylish.

Answer: (C)

2. In terms of impulse and momentum, explain briefly the value of an air bag in a car.

(A) The air bag reduces the total force on the passenger during a collision.
(B) The air bag increases the total force on the passenger during a collision.
(C) The air bag increases the collision time between passenger and car, which reduces the maximum force felt by the passenger.
(D) The air bag decreases the collision time between passenger and car, which reduces the maximum force felt by the passenger.

Answer: (C)

3. We said in section 6.6 that one reason Dick Fosbury was able to develop his "Fosbury Flop" technique for the high jump was the increased padding made available under the high jumper during the landing. In terms of impulse and momentum, explain briefly the value of this increased padding.

(A) The padding reduces the total force on the high jumper during the landing.
(B) The padding increases the total force on the high jumper during the landing.
(C) The padding increases the collision time between high jumper and the ground, which reduces the maximum force felt by the high jumper.
(D) The padding decreases the collision time between high jumper and the ground, which reduces the maximum force felt by the high jumper.

Answer: (C)

4. 2 balls collide in an elastic collision. Which of the following quantities are conserved in the collision? (Circle all that apply)

(A) Momentum?
(B) Kinetic Energy?
(C) Total Energy?

Answers: (A), (B), (C)

5. 2 balls collide in an inelastic collision. Which of the following quantities are conserved in the collision? (Circle all that apply)

(A) Momentum?
(B) Kinetic Energy?
(C) Total Energy?

Answers: (A), (C)

6. A ball collides with a wall and sticks to the wall. What kind of collision is this?

(A) elastic
(B) inelastic
(C) can't be determined without more information

Answer: (B)

7. A ball collides with a wall and bounces off the wall. What kind of collision is this?

(A) elastic
(B) inelastic
(C) can't be determined without more information

Answer: (C)

8. What did "Air Jordan" do to give the illusion of a particularly long hang time?

(A) Jump higher
(B) Push off the floor with more force
(C) Raise his legs while in flight
(D) Put a lot of spin on the ball

Answer: (C)

9. a. If a seat belt were made of a very strong elastic material rather than a rigid strap, how would its performance in a collision be affected?

(A) The elastic seat belt would be more effective in reducing injuries in a collision.
(B) The elastic seat belt would be less effective in reducing injuries in a collision.
(C) There would be no difference.

Answer: (A)

b. Explain the physics.
(longer collision time, less force)

10. A curling stone is sliding on the ice with a certain speed. If the speed is doubled what happens?

(A) The momentum and kinetic energy of the stone both double.
(B) The momentum doubles, the kinetic energy stays the same.
(C) The kinetic energy doubles, the momentum stays the same.
(D) The momentum doubles, the kinetic energy quadruples.
(E) The kinetic energy doubles, the momentum quadruples.

Answer: (D)

11. A ball dropped from a height of 2 meters bounces on a flat surface and rebounds to a height of 2.5 meters. What is the coefficient of restitution?

(A) Exactly 1
(B) Greater than 1
(C) Less than 1
(D) This makes no sense - it violates conservation of energy.

Answer: (D)

12. A ball dropped from a height of 2 meters bounces on a flat surface and rebounds to a height of 2 meters? What is the coefficient of restitution?

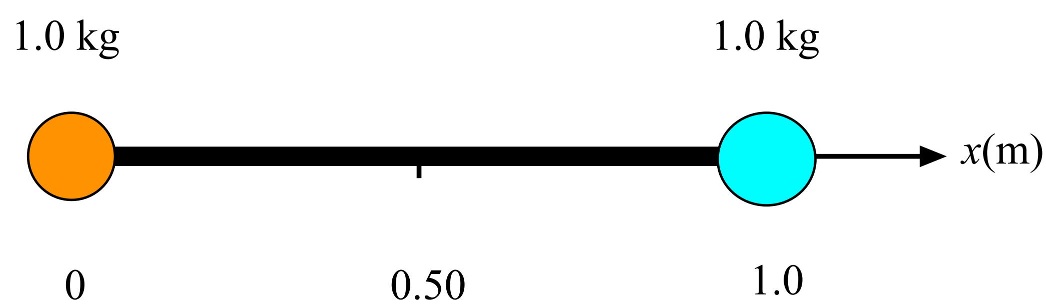
(A) Exactly 1
(B) Greater than 1
(C) Less than 1
(D) This makes no sense - it violates conservation of energy.

Answer: (A)

13. A ball dropped from a height of 2 meters bounces on a flat surface and rebounds to a height of 1.5 meters? What is the coefficient of restitution?

(A) Exactly 1
(B) Greater than 1
(C) Less than 1
(D) This makes no sense - it violates conservation of energy.

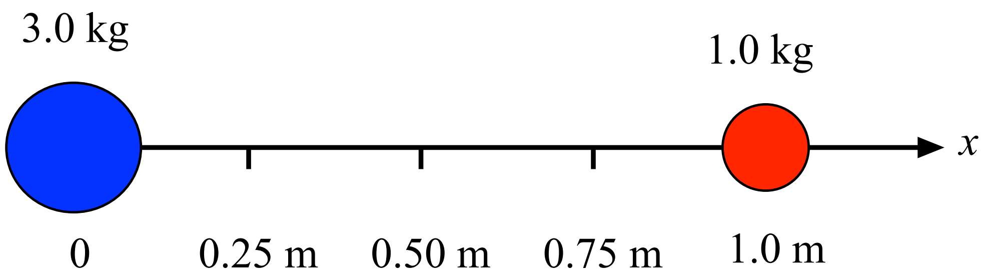
Answer: (C)




14. Two balls of mass one kilogram apiece are connected by a thick rod of mass 2 kilograms. As shown above, the balls are one meter apart at positions of 0 and 1 meter. What is the position of the center of mass of this system?

(A) 0
(B) 0.25 meter
(C) 0.50 meter
(D) 0.75 meter
(E) 1.00 meter

Answer: (C)




15. Two balls of mass one kilogram and 3 kilograms are connected by a thin rod. We'll assume the mass of the rod is so small we can ignore it. As shown above, the balls are one meter apart at positions of 0 and 1 meter. What is the position of the center of mass of this system?

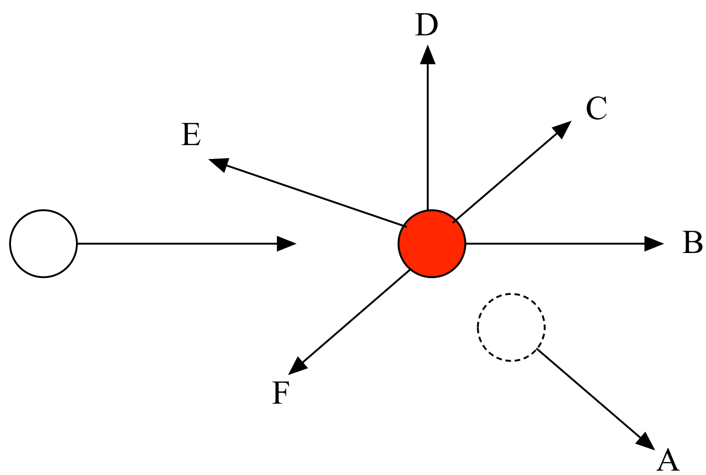
(A) 0
(B) 0.25 meter
(C) 0.50 meter
(D) 0.75 meter
(E) 1.00 meter

Answer: (B)

16. A ball collides with a wall with a certain impulse. In a separate collision, if the impulse is the same but the collision time is doubled, what will happen to the average force of the collision?

(A) The average force will double.
(B) The average force will quadruple.
(C) The average force will stay the same.
(D) The average force will be half the original value.

Answer: (D)




17. The (white) cue ball collides with the (red) 3 ball in billiards, as shown above. After the collision, the cue ball heads off along path A. Which path does the 3 ball take?

Answer: (C)

18. Explain why an air bag in a car might be more useful than a seat belt in preventing injuries during an automobile collision.

19. Explain the physics behind the padding in helmets used in various sports. Name a few of these sports.

20. Explain why an athlete may achieve a better result in a pole vault competition by expertly curving over the bar at the top of the vault.

21. In the discussion of concrete-breaking using martial arts, it was estimated that a novice can generate a hand speed of ~6 meters per second while a black belt expert can generate a hand speed of ~14 meters per second. Assuming the novice is a young adult but the expert is an adult, what other difference between the two will be important in determining what they can break with their hands? (Hint: what else determines the magnitude of the impulse?)

(Answer: smaller hands - less massive for the novice)

22. In the curling video we watched in Chapters 1 and 5, the curler pushed the stone for a while, giving it some initial speed. After the stone had traveled some distance along the sheet, it came to rest.

a. Was energy conserved in this process?

(A) Yes
(B) No

<u>Answer</u>: (A)

Explain.

b. Was kinetic energy conserved in this process?
(A) Yes
(B) No

<u>Answer</u>: (B)

Explain.

c. Was momentum conserved in this process?
(A) Yes
(B) No

<u>Answer</u>: (B)

Explain.

23. Explain how the temperature of a ball will likely affect the Coefficient of Restitution (COR).

24. Besides the high jump, name some other sports in which the position of the center of mass plays a significant role. Explain the role of the center of mass in each case.

25. Give some more examples of collisions in sports; both "good" and "bad" collisions.

26. A basketball with a COR of 0.75 should rebound to a height of -.56 meter if dropped from a height of 1.0 meter. What will happen to the rebound height if the basketball is thrown down instead?

27. Explain why improved padding might have been important in developing the "Fosbury Flop" technique for the high jump.

(The athlete lands on his/her back so better padding is needed for safety.)

28. Explain why the unit of $N \cdot s$ must be equivalent to the unit of $kg \cdot m/s$.

29. What would happen if an air bag did not fully inflate in a collision? Explain the physics.

<u>Exercises</u>

1. A bowling ball of mass 5 kilograms slides down the beginning of the bowling alley with a speed of 4 meters per second. What is the momentum of the ball?

_______________ $kg \cdot m/s$

<u>Answer</u>: 20 $kg \cdot m/s$

2. A tennis racket hits a tennis ball with an impulse of 50 $N \cdot s$ over a time of 0.1 second. What was the force given to the ball by the racket?

____________ Newtons

<u>Answer</u>: 500 Newtons

3. The impulse imparted to a shot of mass 2 kilograms has a magnitude of 40 $N \cdot s$. Assuming that the impulse lasts for 0.5 second, find the magnitude of the average force on the object:

(A) 20 Newtons
(B) 40 Newtons
(C) 80 Newtons
(D) 100 Newtons
(E) 200 Newtons
(F) 400 Newtons

<u>Answer</u>: (C)

4. The impulse imparted to a ball of mass 1.5 kilograms has a magnitude of 45 $N \cdot s$ Assuming that the impulse lasts for 0.25 second, find the change in speed of the ball.

_______________ m/s

<u>Answer</u>: 30 m/s

5. If the momentum of a ball is doubled, by what factor will the kinetic energy change?

(A) 0.5
(B) 1 (no change)
(C) 1.5
(D) 2
(E) 4

<u>Answer</u>: (E)

6. For which case below is the magnitude of the impulse of the racket on the ball the greatest?

(A) A ball of mass 0.5 kilogram hits a racket at a speed of 2 meters per second and sticks to the racket.
(B) A ball of mass 0.5 kilogram hits a racket at a speed of 2 meters per second and bounces back with a speed of 1 meter per second.
(C) A ball of mass 1 kilogram hits a racket at a speed of 1 meter per second and sticks to the racket.
(D) A ball of mass 1 kilogram hits a racket at a speed of 1 meter per second and bounces back with a speed of 1 meter per second.

<u>Answer</u>: (D)

7. If the momentum change in a collision doubles, by what factor has the impulse changed?

(A) 0.5
(B) 1 (no change)
(C) 1.5
(D) 2
(E) 4

<u>Answer</u>: (D)

8. A puck of mass 0.5 kilogram slides along the ice with a speed of 2 meters per second. It hits a second puck with the same mass that had been at rest before the collision and they stick together. Using Conservation of Momentum, find the speed of the two-puck combination.

_____________ meters per second

Answer: 1 meter per second

9. A puck of mass 1 kilogram slides along the ice with a speed of 3 meters per second. It hits a second puck with a mass of 2 kilograms and they stick together. Using Conservation of Momentum, find the speed of the two-puck combination.

____________ meters per second

Answer: 1 meter per second

10. A puck of mass 1 kilogram slides along the ice with a speed of 6 meters per second. It hits a second puck with a mass of 3 kilograms and they stick together. Using Conservation of Momentum, find the speed of the two-puck combination.

____________ meters per second

Answer: 1.5 meters per second

11. A puck of mass 3 kilograms slides along the ice with a speed of 4 meters per second. It hits a second puck with a mass of 1 kilogram that is sliding towards the first puck at a speed of 4 meters per second, and they stick together. Using Conservation of Momentum, find the speed of the two-puck combination.

____________ meters per second

Answer: 2 meters per second

12. A puck of mass 0.5 kilogram slides along the ice with a speed of 2 meters per second. It hits a second puck with same mass that is sliding with a speed of 2 meters per second directly at the first puck. The pucks stick together after the collision. Using Conservation of Momentum, find the speed of the two-puck combination.

____________ meters per second

Answer: 0

13. A puck of mass 0.5 kilogram slides along the ice with a speed of 2 meters per second. It hits a second puck with a mass of 0.5 kilogram that is initially at rest. The first puck comes to stop after the collision.
a. Using Conservation of Momentum, find the speed of the second puck.

____________ meters per second

Answer: 2 meters per second

b. What kind of collision is this?

(A) elastic
(B) inelastic

Answer: (A)

14. A puck of mass 0.5 kilogram slides along the ice with a speed of 2 meters per second. It hits a second puck with a mass of 1.0 kilogram that is initially at rest. The first puck comes to stop after the collision.
a. Using Conservation of Momentum, find the speed of the second puck.

____________ meters per second

Answer: 1 meter per second

b. What kind of collision is this?

(A) elastic
(B) inelastic

Answer: (B)

15. A ball dropped from a height of 1.5 meters rebounds to a height of 1.5 meters. Find the Coefficient of Restitution (COR).

____________

Answer: 1

16. A ball dropped from a height of 1.5 meters sticks to the floor and does not rebound. Find the Coefficient of Restitution (COR).

____________

Answer: 0

17. A ball dropped from a height of 1 meter rebounds to a height of 0.9 meter. Find the Coefficient of Restitution (COR).

____________

Answer: 0.95

18. A ball with a COR of 0.8 is dropped from a height of 2 meters. Find the height of the rebound.

____________ meters

Answer: 1.28 meters

19. A curling stone of mass 20 kilograms is sliding down the sheet with an initial speed of 1.5 meters per second.

a. Find the initial momentum of the stone.

_______________ $kg \cdot m/s$

Answer: 30 $kg \cdot m/s$

b. Find the initial kinetic energy of the stone.

_______________ Joules

Answer: 22.5 Joules

After some time the speed of the stone has decreased to 1 meter per second.

c. Find the change in momentum of the stone.

_______________ $kg \cdot m/s$

Answer: 10 $kg \cdot m/s$

d. Find the change in kinetic energy of the stone.

_______________ Joules

Answer: 12.5 Joules

20. A tennis ball of mass 0.06 kilogram strikes a wall with a speed of 4 meters per second and rebounds with a speed of 3 meters per second.
a. Find the change in momentum of the ball.

_______________ $kg \cdot m/s$

Answer: 0.06 $kg \cdot m/s$

b. Find the impulse imparted to the ball by the wall.

_______________ $N \cdot s$

Answer: 0.06 $N \cdot s$

c. If the collision lasted for 0.05 second, find the average force of the collision.

_______________ Newtons

Answer: 1.2 Newtons

21. A puck of mass 1 kilogram slides along the ice with a speed of 6 meters per second. It hits a second puck with a mass of 3 kilograms. The first puck stops while the second puck travels away with a speed of 2 meters per second.
a. Find the total change in momentum before and after the collision.

_______________ $kg \cdot m/s$

Answer: $0\,\text{kg}\cdot\text{m/s}$

b. Find the total change in kinetic energy before and after the collision.

________________ Joules

Answer: 12 Joules

c. What kind of collision is this?

(A) elastic
(B) inelastic

Answer: (B)

22. A puck of mass 1 kilogram slides along the ice with a speed of 8 meters per second. It hits a second puck with a mass of 2 kilograms. After the collision, the first puck continues moving in the same direction with a speed of 4 meters per second.
a. Find the total momentum before the collision.

________________ $\text{kg}\cdot\text{m/s}$

Answer: $8\,\text{kg}\cdot\text{m/s}$

b. Find the momentum of the first puck after the collision.

________________ $\text{kg}\cdot\text{m/s}$

Answer: $4\,\text{kg}\cdot\text{m/s}$

b. Find the speed of the second puck after the collision.

________________ meters per second

Answer: 2 meters per second

23. A major league baseball has a mass of ~.145 kilogram.
a. Find the momentum of a baseball pitched at 100 miles per hour.

_______________ $kg \cdot m/s$

Answer: 6.48 $kg \cdot m/s$

b. Find the kinetic energy of a baseball pitched at 100 miles per hour.

_______________ Joules

Answer: 145 Joules

24. Rank the momenta of these sports projectiles:

A Pelota throw in jai alai (mass 0.125 kg; speed 150 mph)
B Softball fast pitch (mass 0.185 kg; speed 37 mph)
C Soccer kick (mass 0.45 kg; speed 90 mph)
D Pitched fastball (mass 0.145 kg; speed 100 mph)
E Tennis serve (mass 0.058 kg; speed 120 mph)

Answer: C > A > D > E > B

25. The golf ball VIDEO 6.5 is filmed at a rate of 10,000 frames per second.

a. By counting the number of frames in which the golf ball is in contact with the golf club, estimate the time of the collision.

_______________ second

b. The mass of a golf ball is ~0.045 kilogram. Assuming that the initial speed of the golf ball after the collision with the club was 100 miles per hour, estimate the momentum of the ball.

_______________ $kg \cdot m/s$

c. Estimate the force of the collision.

________________ Newtons

Answers: a. 24 frames - 0.0024 second
b. 2.0 $kg \cdot m/s$
c. 838 Newtons+

26. The eggs in VIDEOS 6.6 and 6.7 were dropped from a height of 1 meter. Using Conservation of Energy, I estimate the speed of the egg just before hitting the floor or pillow was ~4.5 meters per second. (Actually, a little less for the egg-on-pillow because of the thickness of the pillow.)

a. What was the momentum of the egg (mass of 60 grams) just before hitting the floor or pillow?

________________ $kg \cdot m/s$

b. By counting the number of frames (assuming a frame rate of 60 frames/second) in which the egg is in contact with the pillow as it slows down, estimate the time of the collision.

________________ second

c. Estimate the average force of the collision.

________________ Newtons

Answers: a. 0.27 $kg \cdot m/s$
b. ~6 frames – 0.1 second
c. 2.7 Newtons

# CHAPTER 7: Rotational Motion

Figure Skater Michelle Kwan of the U.S. executing a spin

http://teacher.scholastic.com/researchtools/researchstarters/olympics/images/olympics7.jpg

VIDEO 7.1: The long program of Michelle Kwan of the U.S. at the 2004 World Figure Skating Championships

https://digitalcommons.uri.edu/physicsofsports/51/

Select and watch VIDEO 7.1.

## 7.1: Uniform Circular Motion

I'm sure you have seen ice skating performances such as the one you just watched of 5-time world champion Michelle Kwan of the U.S. at the 2004 World Figure Skating Championships in Dortmund, Germany (she won the bronze medal there). Here the moves I want to concentrate on are the parts of the routine when the skater pulls in her arms and/or legs and goes "faster". What does "faster" mean in this case?

The position of Michelle Kwan on the ice during the video was not changing very much if at all. So "faster" does not refer to a change in speed or velocity as we have studied those so far. Instead we might describe her motion as "spinning faster." Clearly, we are talking about a different kind of motion, motion involving going around in a circle, the subject of this chapter. Before we discuss going "faster" in a circle, I want to talk about circular motion when the object or person is <u>not</u> going faster.

Let's look at another ice skating example to illustrate this. Select VIDEO 7.2 and watch a segment of the short program for pair figure skating at the 1984 Winter Olympics from Sarajevo. Kitty and Peter Carruthers of the U.S. won the silver medal for their performances (the medals are based on combined scores from the short program and free skating).

VIDEO 7.2: The short program of pair figure skaters Kitty and Peter Carruthers of the U.S. at the 1984 Winter Olympics

https://digitalcommons.uri.edu/physicsofsports/52/

I want to concentrate on the part of the video when Kitty Carruthers was being held at arm's length and was moving in a circle around Peter. It looked to me that for most of the segment her "spinning speed" was constant. In other words, the time it took her to complete each circle was about the same.

Now this is a different kind of speed than we have studied previously, and in physics we give it a different name (are you surprised?). When we are talking about motion in a circle, we refer to **angular speed** (and **angular velocity** when the direction is important). When the angular speed is constant, as it seems to be for some of this video, then we say the object (Kitty in this case) is traveling with **uniform circular motion**. Here the "uniform" refers to uniform or constant angular speed. By the way, we now know that if we were to further analyze this motion, we would want to know the position of Kitty's ????? as a function of time? (Hint: think about the end of the last chapter.)

Let's assume that Kitty's *angular* speed is constant at least for a while. What can we say about Kitty's acceleration? I'm talking here about the *linear* acceleration we studied previously. Before you answer this, think about what we have discussed before and in a particular, the consequences of Newton's 1st Law.

## QUIZ 7.1

From the pair figure skating video, what can we conclude about Kitty's linear acceleration?

( ) Because her angular speed is constant, the acceleration must be zero.
( x ) Because she is moving in a circle, the acceleration cannot be zero.

Did you choose correctly? Since from Newton's 1st Law, the natural state of a moving object is to travel in <u>a straight line</u> at constant speed (i.e. with constant *linear* velocity), we know that for Kitty to move in a circle there must be a change in her velocity and therefore there must be some acceleration. If there is acceleration, there must be a force. Kitty "wants" to fly off in a straight line (we would call that the "tangential direction") so there must a force pulling or pushing her into the center of the circle to keep her moving in a circle. What is that force?

QUIZ 7.2

What is the force that keeps Kitty moving in a circle?

( ) her weight
( ) the gravitational force
( ) friction
( ) some invisible pushing force
( x ) the tension in Peter's arm
( ) the normal force

I'm sure that Peter would have agreed that he was applying a considerable amount of force to keep Kitty in a circle, the kind of force we call "tension". What if Kitty was traveling "faster", in other words with a greater angular speed? How much force would Peter need then?

QUIZ 7.3

If Kitty's angular speed was greater, how would the tension in Peter's arm be affected?

( ) the tension would be the same
( x ) the tension would be greater
( ) the tension would be less

I hope it is rather clear that a greater angular speed would mean greater force need be applied. What's not so obvious is that this force is proportional to the <u>square</u> of the angular speed.

What else does that force depend on, if anything? You might guess that the force depends on the mass of the object in motion. It should not be surprising that it takes a larger force to spin around a larger mass. Also, you might imagine that the force depends on the size (i.e. radius) of the circle of motion, and it does. It is less obvious that the force is proportional to this radius assuming the angular speed does not change. That means that if Peter pulls Kitty in closer, he would need <u>less</u> force to keep her moving around at the same angular speed.

A sketch of an object (which could be Kitty) rotating in a circle might help to clarify the situation in uniform circular motion:

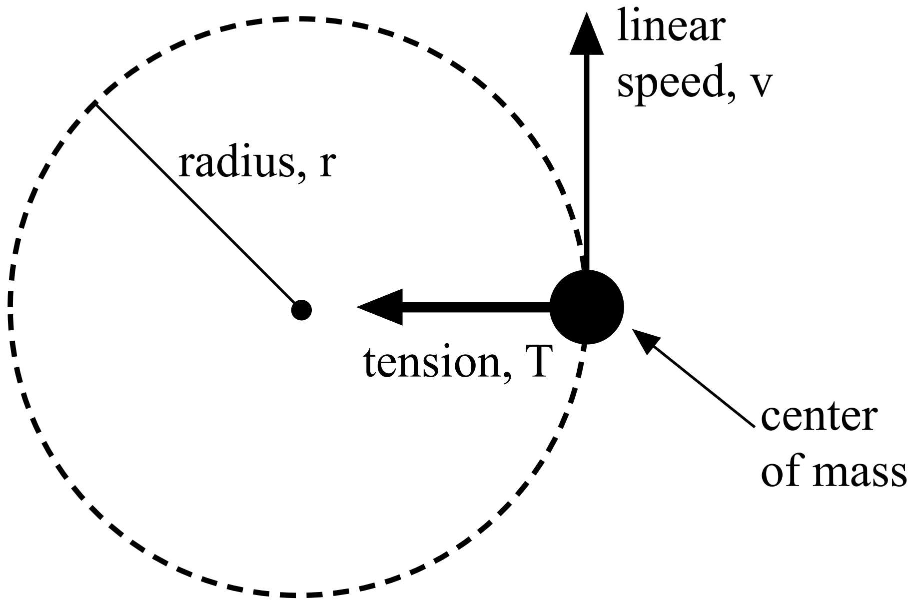



FIGURE 7.1: Sketch of object in uniform circular motion

The force of tension is into the center (actually Peter is pulling at some angle with respect to the ice; but we'll ignore that for now). Kitty has a linear speed, v, with which she would fly off if Peter was not gripping her arm. That's basically uniform circular motion.

Now some specifics:

Angular speed has the (Greek) symbol $\omega$ and the units of radians per second (radian is an alternate unit of angle with 1 radian = 57.3°). One time around a circle of any radius is 360° which is equivalent to $2\pi$ radians = 6.28 radians.

Like the tension in Peter's arm, the force or forces that make an object travel in a circle must add up in such a way that at least part of the total force is pointing into the center of the circle. Whatever these forces are, the total or net force making an object travel in a circle is called the **centripetal force**, $F_{cent}$, and the acceleration into the center of the circle associated with this force (F is still equal to mass times acceleration) is called the **centripetal acceleration**, $a_{cent}$. In equation form, the relation between centripetal force, radius, and angular speed that was given in words above is:

$$F_{cent} = ma_{cent} = m\omega^2 r \qquad \text{Equation 7.1}$$

I want to emphasize that the centripetal force is <u>not a new force</u>. In the skating example it was the tension. In other cases that we'll look at it will be some other force such as friction, weight, ... or a combination of forces that we have already talked about. Noting new!

In some books, a fictitious force that is related to circular motion is also discussed. I won't even name that force or talk about it anymore. It's <u>not real</u> and we don't need it to explain our world or the world of sports.

Looking back at Figure 7.1, it should not be a surprise that if an object is moving in a circle with a greater *angular* speed, ω, then the linear speed, v, at which it would fly off if the centripetal force is removed would also be greater. These speeds are simply related by:

$$v = \omega r \qquad \text{Equation 7.2}$$

QUIZ 7.4

If the angular speed of an object is doubled but the radius is reduced by a factor of two, what happens to the linear speed, v?

( x ) v stays the same
( ) v doubles
( ) v quadruples
( ) v is half the original value
( ) v is 1/4 of the original value

If we substitute for the angular speed, ω, from Equation 7.2 into Equation 7.1 we can rewrite the centripetal force in a commonly used form as:

$$F_{cent} = ma_{cent} = \frac{mv^2}{r} \qquad \text{Equation 7.3}$$

One more thing for now: sometimes it's helpful rather than talking about the speed to instead consider the *time* an object takes to travel in a circle. In particular the time for an object to travel once around a circle, (that is generally referred to in physics as making one **revolution**) is called the **period**, symbol T with a unit of seconds.

Let's estimate the period of Kitty Carruthers from the video. Select the video image again and measure the time it takes her to make two complete revolutions (then divide your answer by 2).

QUIZ 7.5

Find Kitty's period, T, in the pair figure skating video.

_______________ seconds

(Answer: 2 seconds)

I got a period of ~2 seconds. How about you?

With this number, we can find the **frequency** of motion, f (units sec$^{-1}$, called "inverse seconds" or "Hertz", symbol Hz) by:

$$f = \frac{1}{T} \qquad \text{Equation 7.4}$$

$$= \frac{1}{(2\,\text{seconds})} = 0.5\,\text{sec}^{-1} \text{ or Hz in Kitty's case}$$

And we can also find the angular speed, ω, by:

$$\omega = \frac{2\pi}{T} \qquad \text{Equation 7.5}$$

$$= \frac{2\pi}{(2\,\text{seconds})} = 3.1 \text{ radians per second}$$

Now let's look at a couple more examples of uniform circular motion (or at least nearly uniform circular motion) in sports. What I want you to think about in particular is what force (or forces) make up the centripetal force, causing each object to move in a circle.

Select VIDEO 7.3 and watch a short clip from the 2011 Tour de France (eventually won by Cadel Evans of Australia).


VIDEO 7.3:  A segment from the 2011 Tour de France

https://digitalcommons.uri.edu/physicsofsports/53/

QUIZ 7.6

The cyclists ride around a curve in the road. We can approximate this turn as uniform circular motion. What is the centripetal force that keeps the cyclists traveling in a circle?

( ) their weight
( ) the gravitational force
( x ) friction
( ) some invisible pushing force
( ) tension
( ) the normal force

The cyclists turn their front wheels as they go around the turn but it is friction between the tires and the road that provides the centripetal force that keeps them traveling around the curve. The same physics applies when you are driving a car and make a turn in the road.

In the next clip (VIDEO 7.4) we see the result of not enough centripetal force!

VIDEO 7.4: A segment from the 2011 Tour de France

https://digitalcommons.uri.edu/physicsofsports/54/

For our last example, we'll watch again the cycling video from Chapter 3, which showed the Olympic gold medal-winning performance of Marianne Vos of the Netherlands. What is different about the turns the cyclists make from the turn we saw in the Tour de France video? In particular, what is special about the track and why?

s
VIDEO 7.5: Women's point race cycling final at the 2008 Olympic games

https://digitalcommons.uri.edu/physicsofsports/55/

Hopefully you noticed that the track was banked at the turns. There is a reason for this involving centripetal force. We know now from our discussion and from Equation 7.1 that as the angular speed (and therefore the linear speed) of an object such as a bicycle increases, the centripetal force must increase as well (and by the square of the speed) to keep the object moving in a circle. If the speed is great enough then friction in the case of the cyclists will not be enough to keep the bicycles moving in a circle around the turns (as you just observed in the 2nd Tour de France video!). By banking the track, there is another force we have already studied that has a component pointing into the center of the track. What is it?

QUIZ 7.7

By banking the track, what additional force besides friction contributes to the centripetal force? (Remember that part of the force has to be pointing into the center.)

Maybe a diagram of the forces on an object (bicycle, car, what else?) going around a banked curve will help to visualize this good example of circular motion and centripetal force:

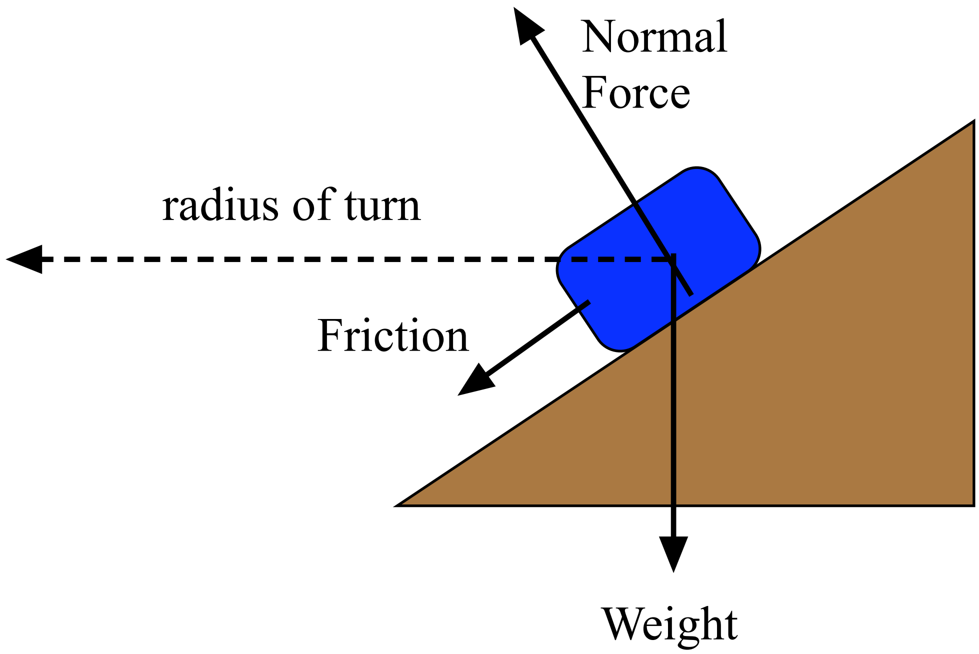



FIGURE 7.2: Sketch of object on a banked curve

Now try to answer the quiz:

( ) the weight
( ) the gravitational force
( ) tension
( x ) the normal force

Hopefully you can see that part of the normal force points towards the center of the track.

## 7.2: Non-Uniform Circular Motion

Of course, not all circular motion is "uniform", i.e. with constant speed. Select VIDEO 7.6 and watch an example of "non-uniform circular motion."

VIDEO 7.6: Hammer throw by Adrian Annus of Hungary at the 2004 Olympic games

https://digitalcommons.uri.edu/physicsofsports/56/

You have just watched a hammer throw by Adrian Annus of Hungary who went on to win the gold medal at the 2004 Olympics in Athens with a throw of 83.2 meters (~273 feet - about how many football field lengths is that?). I think it is clear that the angular speed of the "hammer" (originally the athletes actually threw a sledgehammer) is not constant during the wind-up before the hammer is released. That's the whole idea of the multiple turns that Adrian makes before releasing the hammer - to increase the angular speed (and linear speed) of the hammer as much as possible. So clearly from our previous discussion this is not an example of *uniform* circular motion. Nevertheless, we can still talk about the centripetal force making the hammer go around in a circle before it is released. What is that force?

(Incidentally, a few days after "winning" the gold medal, Adrian Annus tested positive for performance-enhancing drugs and was stripped of his medal.)

QUIZ 7.8

What is the primary force that makes the hammer travel in a circle before it is released?

| | |
|---|---|
| ( ) | the weight |
| ( ) | the gravitational force |
| ( ) | friction |
| ( ) | some invisible pushing force |
| ( x ) | tension |
| ( ) | the normal force |

Hopefully you selected tension, though since the hammer is not spun in a horizontal plane, only part of the tension makes a contribution to the centripetal force (similar to the skating example of Kitty and Peter Caruthers).

Since the angular speed (and angular velocity) is not constant, in analogy with what we now know about linear motion, it seems reasonable to introduce the concept of **angular acceleration**. The symbol for this is the Greek symbol, $\alpha$, and the units are "radians per second squared" (rad/s$^2$) similar to m/s$^2$ for linear acceleration. So now we know that if the angular speed varies, then there is angular acceleration, or more properly we could say that the angular acceleration is not zero. Angular velocity and angular acceleration are both vectors in physics. That means again that both have magnitude and direction so they can also be positive or negative, but that is a detail we don't need to be concerned with right now.

Let's look at another example from sports and you decide if there is any (non-zero) angular acceleration. You want to look for an object that is moving in some kind of a circle with an angular speed that is varying. Select and watch VIDEO 7.7.

VIDEO 7.7: Golf shot by Tiger Woods

https://digitalcommons.uri.edu/physicsofsports/57/

You just watched a golf shot by Tiger Woods at the 1996 Greater Milwaukee Open.

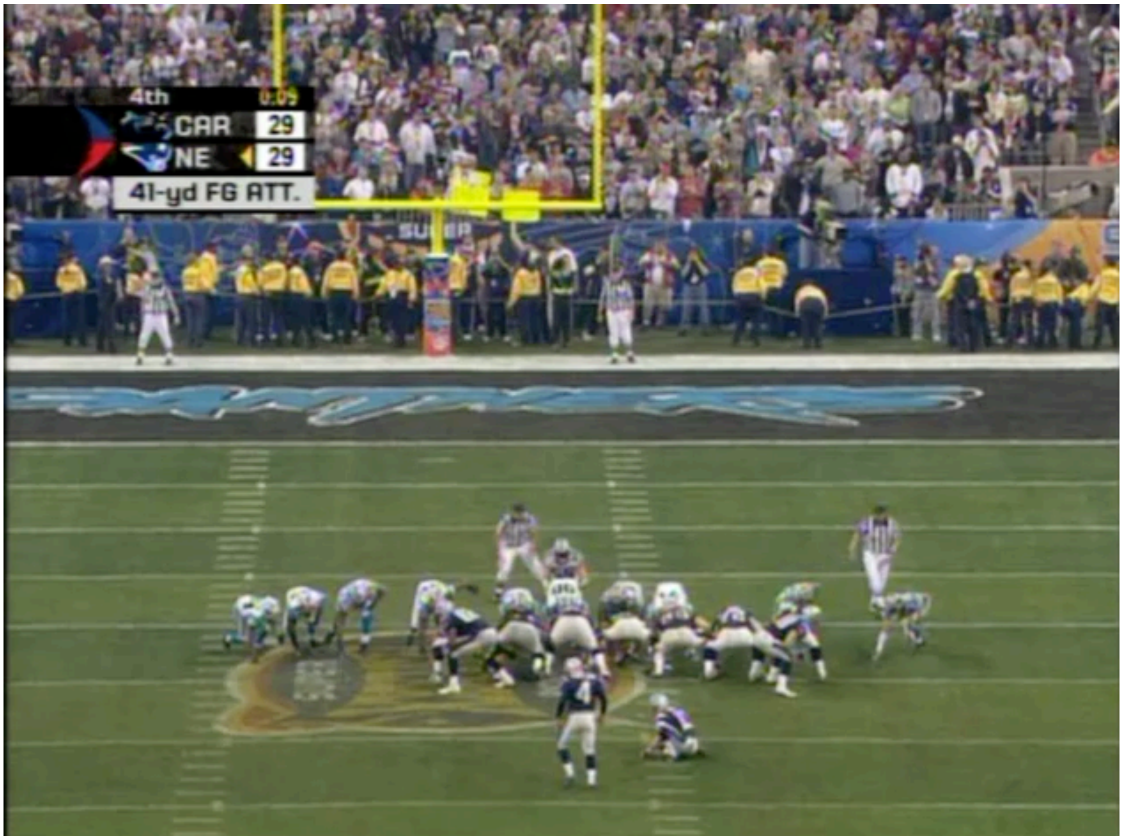
QUIZ 7.9

Did you observe any object undergoing angular acceleration in this video clip?

( x ) yes
(   ) no

A loaded question, obviously. I hope you noticed the motion of the golf club. Tiger swung it back and above his shoulder, then he swung it down to hit the golf ball as hard as possible (or maybe with control and not as hard as possible, I'm not sure). So the club was at rest briefly at its highest point; a short time later it hit the golf ball traveling with its greatest angular speed. So clearly going from rest to traveling around in circular motion the club had to experience angular acceleration. Just like in the linear case we studied earlier, if something goes from not moving to moving, then acceleration has to be involved. I'm sure you can think of several other similar examples involving angular acceleration of clubs, rackets, bats, etc.

Here's one more good sports example of angular acceleration (VIDEO 7.8):




VIDEO 7.8: Field Goal by Adam Vinatieri of the New England Patriots during Super Bowl XXXVIII

https://digitalcommons.uri.edu/physicsofsports/58/

You just watched Adam Vinatieri kick the game winning field goal as the New England Patriots defeated the Carolina Panthers in Super Bowl XXXVIII. Did you see an object undergoing angular acceleration? This example was not quite as obvious as the golf club. What I had in mind was the kicker's right leg. Vinatieri swung it back as far as possible, then accelerated it (in the angular sense), swiveling it about his hip until it made contact with the football at maximum angular speed. Can you think of more sports examples like this?

# 7.3: Torque

FIGURE 7.3: Man riding a penny-farthing bicycle

http://www.feministe.us/blog/wp-content/uploads/2010/11/old-bike-224x300.jpg

In the last section I introduced the concept of angular acceleration. When we were discussing linear motion, one of the next steps after discussing linear acceleration was to present Newton's Laws. One way of looking at Newton's 1st Law in particular is to say that if there is acceleration then there must be a force (or forces) causing this acceleration. What about in the rotational case? Does the same idea and/or law apply?

Basically, the answer is "Yes". As you may have already noticed, there are pretty good analogues in rotational motion to almost all of the concepts and equations we learned about when we discussed linear motion - speed, velocity, acceleration, and now force. For rotational motion we need a "rotational force", called in physics **torque**. The symbol for torque is $\tau$ ("tau") and the unit is the Newton-meter ( $N \cdot m$ ). One way of stating Newton's 1st Law for rotational motion is that if an object undergoes angular acceleration, then there must be a torque (or torques) acting on the object. Torque is proportional to the angular acceleration it produces just like force is proportional to (linear) acceleration.

QUIZ 7.10

A torque of 15 $N \cdot m$ is applied to a tennis racket, causing it to accelerate at 3 $rad/s^2$. If the torque is increased to 45 $N \cdot m$ what will be the angular acceleration of the racket?

_________________ $rad/s^2$

(Answer: 9 $rad/s^2$)

So torque causes angular acceleration. Let's consider another example. You hop on the bicycle shown in the figure at the beginning of this section. You and the bicycle are at rest (before you fall over!). You want to get the bike moving, which means that the wheels need to have some angular speed. Since the wheels are initially at rest, that calls for angular acceleration which requires some torque. You push on the pedal. The wheel starts to turn, accelerating at some rate. Clearly the push you made generated torque on the wheel. Now you want to increase the angular acceleration of the wheels so that you and the bicycle will accelerate along the road at a greater rate. What do you do?

QUIZ 7.11

To increase the angular acceleration of the bicycle wheel, what should you do?

( x ) You should push on the pedals with greater force.
( ) You should push on the pedals with less force.
( ) There is nothing you can do to change the angular acceleration.

I hope you selected the correct answer. I think it is pretty clear that more force on the pedals will lead to greater angular acceleration so that means that greater force applied to a rotating object means greater torque. Is that all that matters? You might guess that the answer is "No."

Now you hop on a more modern bicycle, as shown below. On this type of bike, how else could you increase your angular acceleration? You probably know that the solution is to change gears. By switching to a higher gear, the torque you are applying for a given force is greater, so your angular acceleration will increase.


FIGURE 7.4: Modern bicycle

http://www.sciencephoto.com/image/215421/large/H1000660-Bicycle_gears-SPL.jpg

What actually happens when you switch to a higher gear? (I'm thinking of the front derailer here.) It causes the chain to be moved to a new position around the wheel at a larger radius than for the smaller gears. So by applying force at a greater radius or distance from the rotation axis of a rotating object, the torque is greater. So torque depends on the force, F, applied and the distance or radius, r, at which it is applied (torque also depends on the direction of the applied force but we'll skip over that at least for now). In the basic case, the relation is quite simple and is given by the following equation:

$$\tau = rF \qquad \text{Equation 7.5}$$

So anytime you observe angular acceleration in sports or otherwise, there is at least one force being applied at some radius resulting in a torque given by the above equation. To swing a golf club, tennis racket, ... to kick a football or soccer ball, ... force and torque are generated by some muscles in the body. Other examples from sports: the tight spiral of a football pass, the curve ball in baseball, the somersault off a diving board. All these rotations or circular motions involve forces and torques. Can you think of more?

## 7.4:  Rotational Mass

For linear motion we know that the force is proportional to the acceleration. For linear motion the missing quantity that completes Newton's 2nd Law is the mass. One way of thinking about this equation (F = ma) is to say that for a greater mass, a greater force is required to produce the same acceleration. What about rotational motion? We have stated in the previous section that rotational force (torque) is proportional to angular acceleration. What is the missing quantity in this case? Is it mass? Not quite. To complete a rotational version of Newton's 2nd Law, we need to introduce **rotational mass**, also known as **rotational inertia** or **moment of inertia**. The symbol for this is "I" and the unit is kilograms times meters squared ($\mathrm{kg \cdot m^2}$). Now we can write down an equation relating the rotational quantities we have been discussing:

$$\tau = \mathrm{I}\alpha \qquad \text{Equation 7.6}$$

QUIZ 7.12

If the rotational mass of an object is increased, what can we say about the torque needed to maintain the same angular acceleration?

( ) The torque should remain the same.
( x ) The torque should be increased.
( ) The torque should be decreased.

Hopefully you can see that the effect of increasing rotational mass for rotational motion is the same as increasing the mass for the linear case we have discussed previously.

But what is rotational mass? To learn more about this, we'll take a look at a special kind of baseball bat. You may have heard that occasionally a baseball player is caught using an illegal "corked bat". This bat, such as the cut-open one shown in the picture below, has part of the top of the bat drilled out and replaced by cork which is lighter that the original wood.

FIGURE 7.5:  Cut-out view of a corked baseball bat

http://www.acs.psu.edu/drussell/bats/images/corked-bat-3.jpg

Now why do you think a baseball player would choose to take a chance and illegally modify his bat this way?

QUIZ 7.13

Why would a baseball player use a corked bat?

( x ) to make it easier to swing the bat
(   ) to make it harder to swing the bat

Of course, "easier" is the correct answer. What is meant by easier? What I had in mind is that with a corked bat the player can obtain the <u>same</u> bat speed from the same angular acceleration with <u>less</u> force and torque. If we keep this in mind when we look back at Equation 7.6, this means that the rotational mass of an object must be related to the mass since a smaller rotational mass means less torque to obtain the same angular acceleration, just as we expected for the corked bat.

But is the mass of the swinging (rotating) object the whole story in terms of the rotational mass? You might have guessed that the answer is "No". There's more to it.

There are some circumstances when a baseball player chooses to reduce the rotational mass of his bat (legally!) in order to increase its maneuverability. Maybe you have heard of the hitter being "down in the count". Usually this means that he has two strikes and one or no balls. When that is the case, the hitter often wants to "protect the plate," meaning that he wants to be ready to make contact with the ball rather than take a third strike. How does he do this? This would not be a good time for the hitter to call "time" and change bats to an illegally corked one! Instead, he "chokes up" on the bat, moving his hands a little up the handle of the bat so the pivot point or axis of rotation is a little closer to the end of the bat. (The image below shows baseball legend Hank Aaron in a rather extreme example). What does the player gain by doing this?

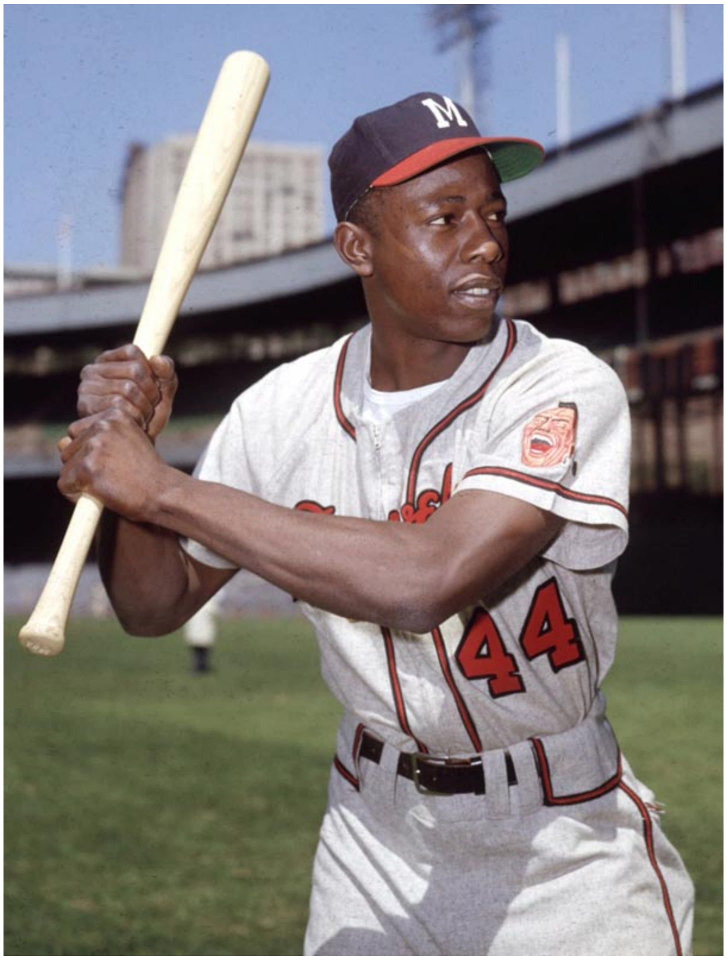




FIGURE 7.6: Baseball legend Hank Aaron "choking up" on a baseball bat

http://2.bp.blogspot.com/_xGU3W7Ugqn4/TUyHk3F3uGI/AAAAAAAAF98/bKt3Ax5QFJE/s1600/hank-aaron.jpg

QUIZ 7.14

Choking up on a bat has what effect?

( x ) It makes the <u>average</u> position of the mass of the bat closer to the axis of rotation.

(   ) It makes the <u>average</u> position of the mass of the bat further from the axis of rotation.

By getting the average position of the mass of the bat closer to the axis, the bat is more maneuverable, "easier" to swing and this allows the batter to make last second adjustments in order to make contact with the ball. In keeping with our earlier discussion of corked bats, changing the average mass position or mass distribution must be also be connected to the rotational mass.

So for rotating objects it matters not just how much mass there is but also where the mass is located or distributed. For a simple object such as point mass, m, circling at some radius, r, the equation for the rotational mass or moment of inertia, I, is relatively simple:

$$I = mr^2 \qquad \text{Equation 7.7}$$

If you remember the video from earlier in the chapter, the hammer used in the hammer throw would be a good approximation to this simple case. For more complicated rotating objects such as bats, arms, legs, etc. the rotational mass is still proportional to the mass and to the square of some average radius or distance, with the constant of proportionality depending on the shape of the object.

FIGURE 7.7: Athlete swinging a "hammer"

http://www2.pictures.gi.zimbio.com/Australian+Athletics+Championships+Day+3+HtdWBM3xZ2el.jpg

QUIZ 7.15

The woman's hammer has a mass of 4 kilograms and a length of ~1.2 meters (~2.0 meters including the arm length).

a. If the mass was increased by 50%, by what percentage would the rotational mass increase?

( ) 25%
( x ) 50%
( ) 75%
( ) 100%
( ) 125%
( ) 150%

b. If instead the total length was increased by 50%, by what percentage would the rotational mass increase?

( ) 25%
( ) 50%
( ) 75%
( ) 100%
( x ) 125%
( ) 150%

The rotational mass can be an important design consideration in various items of sports equipment and in the choices made by the athletes who use them. In tennis, for example, a lower rotational mass of a tennis racket (which could be achieved by reducing the mass of the head or the handle of the racket) will make the racket "easier" to swing and more maneuverable similar to the corked bat (but legal!). On the other hand, for a player with a powerful stroke (there's that word "power" again - it works for rotating objects also), a greater rotational mass will provide the racket with more force when it strikes the tennis ball.

Another good example: the snow ski can be made more maneuverable or more stable by controlling the rotational mass of the ski. The issue in this case is how easy or hard it is to twist the ski about a vertical axis through the ankle. For both the tennis racket and the snow ski, the rotational mass in equipment specifications is referred to as the "swing weight."

FIGURE 7.8: Men's Giant Slalom

https://ichef.bbci.co.uk/live-experience/cps/1024/cpsprodpb/5BBE/production/_105668432_philpnight_getty.jpg

QUIZ 7.16

a. Given two sets of skis with different swing weights, which skis would be more stable against twisting about the ankle?

( ) The skis with the smaller swing weight.
( x ) The skis with the larger swing weight.
( ) Swing weight should not affect the stability of skis.

b. What would be the best way to increase the swing weight of a ski?

( ) Decrease the mass of the ski uniformly.
( ) Increase the mass of the ski uniformly.
( ) Decrease the mass at the tip and tail of the ski.
( x ) Increase the mass at the tip and tail of the ski.

Can you think of more examples in which the rotational mass of a swinging or rotating sports object (which could be a body part!) is important?

## 7.5: Angular Momentum

Finally, in the last main section of this chapter, we return to the opening video of Michelle Kwan skating around in a circle (VIDEO 7.1) and examine this with the physics we have just learned. At the beginning of the video she is rotating around with her arms and legs more or less extended. Towards the end of the routine, she rearranges her arm and leg positions and she spins faster.

From a physics point of view, we describe her motion as follows: she starts out with some initial angular speed, we'll call that $\omega_i$, "i" for initial. She also starts out with some initial body pose with a corresponding (and fairly complicated) rotational mass we'll call $I_i$. When she pulls her legs and arms in somewhat, her final rotational mass, $I_f$, will decrease while her angular speed, $\omega_f$, increases. So as rotational mass goes down, angular speed goes up.

Maybe this reminds you of an equation (Equation 6.4: $p_i = p_f$ or $m_i v_i = m_f v_f$) and concept from the last chapter (Conservation of (Linear) Momentum). In that case, if the mass decreases during a collision or some other interaction, then the (linear) speed, v, increases. Do you see the similarity to the rotational case?

By now we are used to substituting variables from the linear motion to create the analogous variables and equations of rotational motion. It follows that the combination of rotational mass and angular speed is the **angular momentum** with symbol L and unit $kg \cdot m^2/s$:

$$L = I\omega \qquad \text{Equation 7.8}$$

Angular momentum is conserved in a number of cases such as the skating example, when the external torque is zero (we needed the external force to be zero to conserve linear momentum in Chapter 6). When it is conserved, then we can write:

$$L_i = L_f \quad \text{or} \quad I_i \omega_i = I_f \omega_f \qquad \text{Equation 7.9}$$

For the case of Michelle Kwan in the video, its more than we will attempt in this course to figure changes in rotational mass, but we can do a rough calculation of her motion. From the video I estimate that initially it took her ~1 second to make a revolution (can you come up with a better number than that?), which corresponds to an angular speed (using Equation 7.4) of:

$$\omega_i = \frac{2\pi}{T} = \frac{2\pi}{1\sec} = 6.3 \text{rad/s}$$

We'll round that off to 6 rad/s. What about her rotational mass?

QUIZ 7.17

For Michelle Kwan, assume that her rotational mass decreased by 50% (to 50% of the initial value) during her spin. With an initial angular speed of 6 rad/s, what will be her final angular speed?

_____________ rad/s

(Answer: 12 rad/s )

This change would decrease her period from ~1 second to $\frac{2\pi}{12} \approx 0.5$ second. Somewhat reasonable but probably we overestimated her rotational mass change.

A couple of things we need to point out: First, ω is really angular velocity, not speed. Since velocity is a vector, angular momentum must be a vector as well. Therefore, it has a direction and can be negative or positive, just like any vector. Second: at the end of the skating video, Michelle Kwan came to rest by applying pressure from her skates onto the ice. This provided an external torque so we should not expect angular momentum to be conserved any longer, and it clearly isn't since she stops.

I can think of a couple of other sports in which the athlete changes his or her body shape or alignment in order to affect his or her rotation: diving and gymnastics. Can you come up with any other examples?

**Angular Momentum Conservation** is also very important in enhancing the stability of various projectiles. By imparting a spin to a projectile in flight, the direction is stabilized since it would require an external torque to change the angular momentum, including its direction. This helps to explain the distance and accuracy of footballs thrown with tight spirals (the strength and skill of the quarterback is also important!). Likewise, most gun barrels are manufactured with a set of twisting grooves which impart a spin to the bullets for the same reason. An example of the barrel of the 105 mm Royal Ordnance L7 tank gun is presented in Figure 7.9.

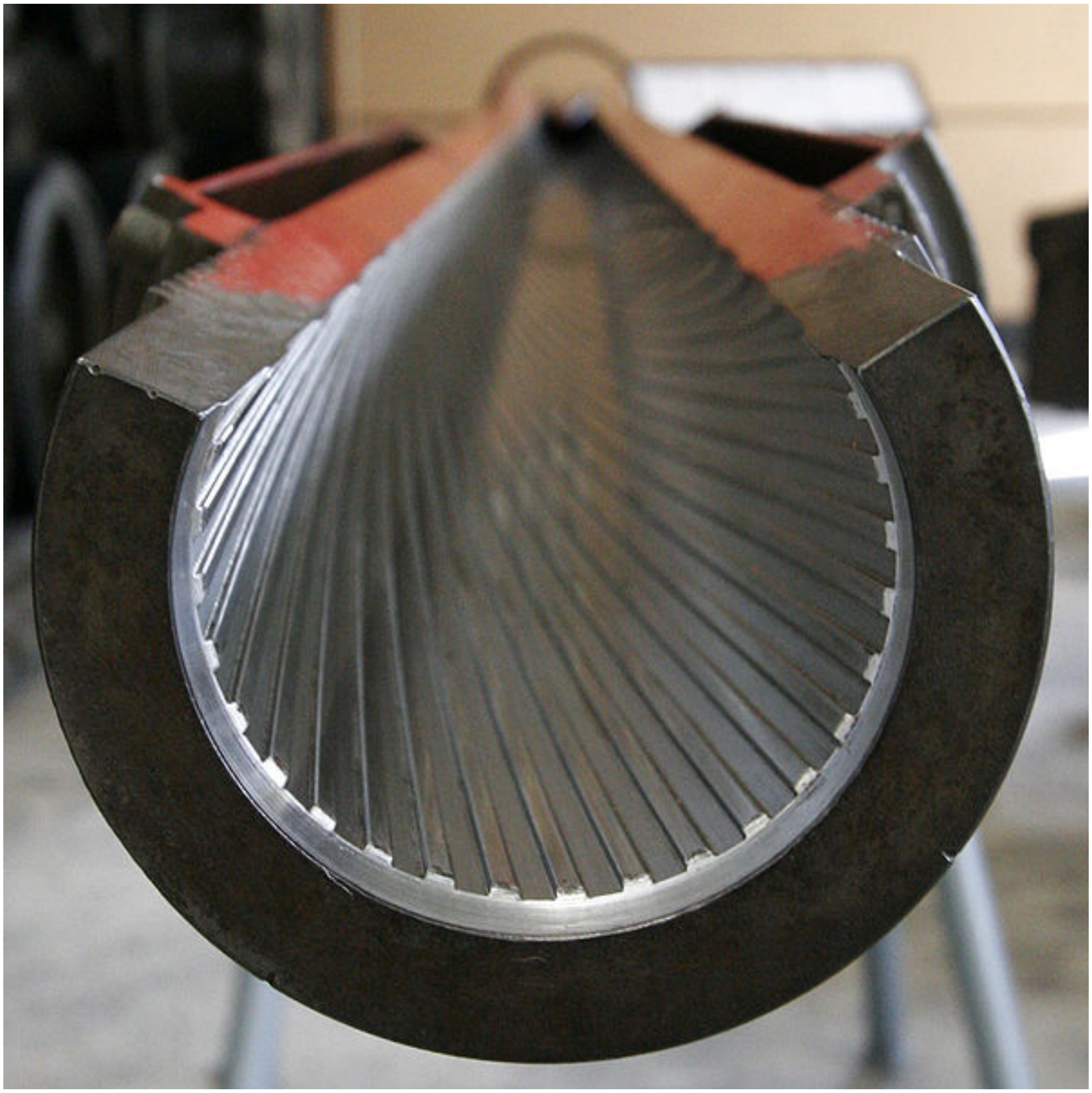


FIGURE 7.9: Cut away barrel of a 105 mm tank gun

https://upload.wikimedia.org/wikipedia/commons/b/b2/105mm_tank_gun_Rifling.jpg

The process of imparting grooves in the barrel of a gun is in fact called "rifling." Such a groove pattern is characterized by the "twist rate" which is the distance the projectile travels along the barrel (in inches or in centimeters) in order to complete one revolution. Can you think of more examples of spinning projectiles?

## 7.6: Bouncing and Rolling Balls

Another topic in sports that is connected to rotational motion is what happens when a rotating ball is in contact with or collides with another ball or surface. (We'll discuss rotating balls "colliding" with air in the next chapter.) A few good examples are:

1. In billiards, hitting the cue ball off center ("English", "side", "draw", "follow"). This causes the cue ball to spin as well as travel forward, which has important consequences when it hits another ball or the rail.
2. In bowling, a ball released with a well-designed rotation (spin) will start out straight and then "hook" towards the pins.
3. In basketball, an effective pass from the point guard to another player on his team is the bounce pass, sometimes with spin added to change the direction after it hits the floor. Also, the spin of a basketball can be important in shots at the basket.

That's all I have time to say about this topic in this ebook. Certainly, a good one for further study.

## Chapter 7 Homework

Questions

1. What makes it easier to swing a tennis racket?

(A) gripping the end of the racket
(B) shortening up the grip along the handle

Answer: (B)

2. Will adding lead tape to the end of a tennis racket make it easier or harder to swing?

(A) easier
(B) harder

Answer: (B)

3. How will adding lead tape to the end of a tennis racket affect its swing weight?

(A) This will have no effect on the swing weight.
(B) This will cause the swing weight to increase.
(C) This will cause the swing weight to decrease.

Answer: (B)

4. A tether ball swings around a pole at constant speed. What is the primary centripetal force keeping the ball in a circle?

(A) the weight
(B) the gravitational force
(C) friction
(D) some invisible pushing force
(E) tension
(F) the normal force

Answer: (E)

5. An automobile on a level road turns a corner at constant speed. What is the primary centripetal force keeping the car traveling in a circle around the turn?

(A) the weight
(B) the gravitational force

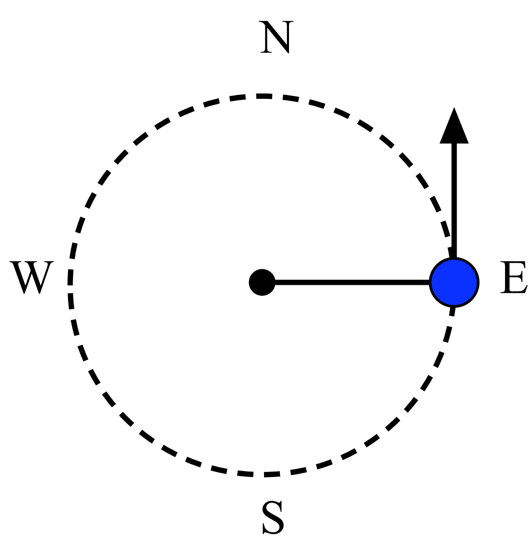
(C) friction
(D) some invisible pushing force
(E ) tension
(F) the normal force

Answer: (C)

6. A figure skater is spinning around on the ice with his arms outstretched. Suddenly he brings his arms close to his body. What will happen?

(A) His angular speed will increase.
(B) His angular speed will decrease.
(C) There will be no change in his angular speed.

Answer: (A)




7. A ball on a string is rotating in uniform circular motion in a counterclockwise direction as seen from above (ignore the effects of gravity and air resistance). At that exact moment, in what direction (N,S,E, or W) is the centripetal force on the ball?

(A) N
(B) S
(C) E
(D) W

Answer: (D)

8. If everything else remains the same, what will happen to the angular momentum of an object if the angular speed is reduced?

(A) The angular momentum will remain unchanged.
(B) The angular momentum will increase.
(C) The angular momentum will decrease.

Answer: (C)

9. To turn a very tight nut with a wrench, what wrench would be more effective:

(A) short wrench
(B) long wrench
(C) same - doesn't matter

Answer: (B)

10. Some baseball players "choke up" on a bat before they swing. Why?

(A) This decreases the rotational mass so it is harder to swing the bat.
(B) This decreases the rotational mass so it is easier to swing the bat.
(C) This increases the rotational mass so it is harder to swing the bat.
(D) This increases the rotational mass so it is easier to swing the bat.

Answer: (B)

11. Given two sets of skis with different swing weights, which skis would be more maneuverable?

(A) The skis with the smaller swing weight.
(B) The skis with the larger swing weight.
(C) Swing weight should not affect the maneuverability of skis.

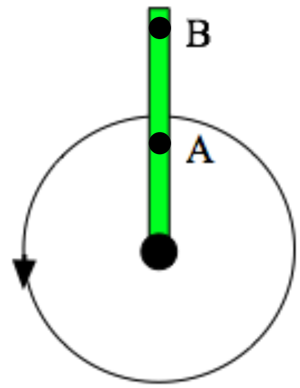
Answer: (A)

12. A student sits on a spinning piano stool with her arms folded. When she extends her arms, which of the following occurs?

(A) She increases her rotational mass, thereby increasing her angular speed.
(B) She increases her rotational mass, thereby decreasing her angular speed.
(C) She decreases her rotational mass, thereby increasing her angular speed.
(D) She decreases her rotational mass, thereby decreasing her angular speed.

(E) Both her rotational mass and her angular speed remain constant.

Answer: (B)




13. A rod is rotating around a fixed axis. The angular acceleration is 0. Consider points A and B on the rod. Compare the angular speeds:

(A) The angular speed at point A is less than that at point B.
(B) The angular speed at point A is greater than that at point B.
(C) The angular speed at point A is the same as that at point B.

Answer: (C)

| | |
|---|---|
|  |  |
| A | B |

14. Given the two yoga "tree" poses shown above, for which is the rotational mass greater; in other words which pose is more stable against tipping over?

Answer: (B)

15. In Figure 7.2, which depicts an object circling a track on a banked curve, does the weight of the object contribute to the centripetal force keeping the object in a circle?

(A) Yes
(B) No

<u>Answer</u>: (B)

http://english.peopledaily.com.cn/200610/08/images/xin_391003081007548166O7.jpg

16. Why does a tight rope walker sometimes hold a long pole?

(A) It increases his rotational mass, thereby increasing the torque needed to make him accelerate (start to tip).
(B) It decreases his rotational mass, thereby increasing the torque needed to make him accelerate (start to tip).
(C) It increases his rotational mass, thereby decreasing the torque needed to make him accelerate (start to tip).
(D) It decreases his rotational mass, thereby decreasing the torque needed to make him accelerate (start to tip).
(E) The pole is just for show; it doesn't affect the stability of the walker.

<u>Answer</u>: (A)

17. A cyclist skids while trying to make a turn on a wet road. Explain the physics as it relates to circular motion and centripetal force.

18. Give more examples in which some kind of circular motion of a sports projectile is important.

19. Give more examples of in which some kind of circular motion of an athlete is important.

20. To calculate the rotational mass of the hammer about the athlete's axis of rotation depicted in Figure 7.7, we would need to know the mass of the hammer, the length of the hammer, and what else?

Answer: the length of the athlete's arms

21. Give more examples in which the rotational mass of a swinging or rotating sports object is important. (Besides the hammer, skis, and the baseball bat.)

(Answers: tennis, football, basketball, ...)

22. Give more examples (besides skating, diving, and gymnastics) in which the athlete changes his or her body shape or alignment in order to affect his or her rotation.

(Answers: skiing and snowboarding and skateboarding on a half pipe, ski jumps, motorcycle jumps ...)

23. Besides the football pass and bullets, give more examples of spinning projectiles in sports.

(Answers: baseball curve ball, tennis ball serves and shots, ping pong, archery, ...)

24. A ball is spinning around an axis with constant angular speed.
a. Is the linear speed of the ball constant?
(A) Yes
(B) No

b. Is the linear velocity of the ball constant?
(A) Yes
(B) No

c. Is the angular acceleration equal to 0?
(A) Yes
(B) No

d. Is the linear acceleration equal to 0?
(A) Yes
(B) No

Answers:
a. A
b. B
c. A
d. B

25. Explain why a banked track is used in auto racing.

26. A tennis player serves a tennis ball to the opponent. What kind of angular velocity does her arm motion represent?

(A) uniform angular velocity
(B) non-uniform angular velocity
(C) the angular velocity is 0

Answer: (B)

26. A baseball player hits a home run. What kind of angular velocity does the bat motion represent?

(A) uniform angular velocity
(B) non-uniform angular velocity
(C) the angular velocity is 0

Answer: (B)

27. A speed skater rounds a turn at constant speed. What kind of angular acceleration does this motion represent?

(A) uniform angular acceleration
(B) non-uniform angular acceleration
(C) the angular acceleration is 0

Answer: (C)

28. A heavy bowling ball has a mass of ~7 kilograms. A player releases the ball down the alley with a certain linear speed, v. A second bowler with longer arms releases an identical ball with the same speed. Compare the rotational mass of the arm/ball combination in both cases:

(A) The rotational mass of the arm/ball of the player with shorter arms is greater.
(B) The rotational mass of the arm/ball of the player with longer arms is greater.
(C) The rotational mass is the same in both cases.

Answer: (B)

29. A heavy bowling ball has a mass of ~7 kilograms. A player releases the ball down the alley with a certain linear speed, v. A second bowler with longer arms releases an identical ball with the same speed. Compare the angular speeds of the arm-ball combination about the shoulder joint just before the ball is released:

(A) The angular speed for the player with shorter arms is greater.
(B) The angular speed for the player with longer arms is greater.
(C) The angular speed is the same in both cases.

Answer: (A)

30. A parent pushes a child around on a merry-go-round at constant angular speed. The parent releases the merry-go-round and it comes to a stop.

a. Is angular momentum conserved in this process?

(A) Yes
(B) No

Answer: (B)

b. Explain.

31. Consider the golf swing just before and after the collision with a golf ball. Assuming that angular momentum is conserved during the collision, compare the angular speed of the club just before and after the collision with the golf ball.

(A) The angular speed of the golf club is the same before and after the collision.
(B) The angular speed of the golf club is greater after the collision.
(C) The angular speed of the golf club is less after the collision.

Answer: (C)

32. Besides bicycle and auto racing, name another sport that uses a banked curve.
(roller derby, speed skating, bobsled)

## Exercises

1. A car going around a curve of radius r and speed v experiences a centripetal acceleration of $a_c$. What is the acceleration if it goes around a curve of radius 3r at speed 2v?

(A) (2/3) $a_c$
(B) (4/3) $a_c$
(C) (2/9) $a_c$
(D) (9/2) $a_c$
(E) (3/2) $a_c$

Answer: (B)

2. A ball is moving with uniform circular motion with a radius of 2 meters. The magnitude of the centripetal acceleration of the particle is 8.0 $m/s^2$. Find the speed of the particle:

(A) 2 meters per second
(B) 2.8 meters per second
(C) 4 meters per second
(D) 5.7 meters per second
(E) 8 meters per second

Answer: (C)

3. An object of mass m is undergoing uniform circular motion with radius r and speed v. The magnitude of the centripetal force needed to produce this motion is 10 Newtons. If m, r, and v are all tripled, what force will be needed to maintain uniform circular motion?

(A) 10 Newtons
(B) 30 Newtons
(C) 60 Newtons
(D) 90 Newtons
(E) 180 Newtons
(F) 270 Newtons
(G) 540 Newtons

Answer: (D)

4. A force of 10 Newtons is applied to a tennis racket at a distance of 0.75 meter from the end of the racket. How much torque does that cause about the handle of the racket?

_______________ N· m

Answer: 7.5 N· m

5. Two children are sitting on opposite sides of a seesaw; a boy of mass 80 kilograms and a girl of mass 40 kilograms.

a. If the seesaw is balanced (and not moving), what can you say about the torques given by each child on the seesaw about its axis?

(A) The torques are identical.
(B) The torques are the same in magnitude but opposite in direction.
(C) The torque due to the 80 kilogram boy is greater.
(D) The torque due to the 40 kilogram girl is greater

b. If the 80 kilogram boy is sitting 1 meter from the center of the seesaw, how far from the center is the 40 kilogram girl sitting?

_____________ meters

Answers: a. B
b. 2 meters

6. A force of 5 Newtons is applied perpendicular to a bat at a distance of 0.5 meter from the end of the bat. How much torque does that cause about the end of the bat?

(A) 0.5 N·m
(B) 1.25 N·m
(C) 2.5 N·m
(D) 5.0 N·m
(E) 10 N·m

Answer: (C)

7. Which force/wrench combination supplies the most torque?

(A) 5 Newtons with a wrench of length 10 centimeters
(B) 5 Newtons with a wrench of length 20 centimeters
(C) 10 Newtons with a wrench of length 10 centimeters
(D) 10 Newtons with a wrench of length 20 centimeters
(E) 20 Newtons with a wrench of length 5 centimeters
(F) 20 Newtons with a wrench of length 10 centimeters
(G) 20 Newtons with a wrench of length 20 centimeters

Answer: (G)

8. An ice skater with her arms outstretched has a rotational mass of 2.4 $kgm^2$ and spins with an angular speed of 20 radians per second initially. When she folds in her arms, her rotational mass changes to 1.2 $kgm^2$. What is her final angular speed?

(A) 10 radians per second
(B) 14.1 radians per second
(C) 20 radians per second
(D) 28.3 radians per second
(E) 40 radians per second

Answer: (E)

9. A man stands on a platform with one arm extended and holding a block. The combined rotational mass of him plus weight in this position is 12 $kgm^2$. The platform is rotating with an angular speed of 10 radians per second. If he brings his arm and block in towards his body, his rotational mass drops to 8 $kgm^2$. Find his new angular speed.

(A) 3.33 radians per second
(B) 6.67 radians per second
(C) 10 radians per second
(D) 15 radians per second
(E) 30 radians per second

Answer: (D)

10. A skater rotates through an angular displacement of magnitude 180 degrees. How many radians is that?

(A) $\pi/4$ radians
(B) $\pi/2$ radians
(C) $\pi$ radians
(D) $3\pi/2$ radians
(E) $2\pi$ radians
(F) $4\pi$ radians

Answer: (C)

11. A skater rotates through an angular displacement of magnitude 180 degrees. How many revolutions is that?

(A) 1/4
(B) 1/2
(C) 1
(D) 1.5
(E) 2
(F) 4

Answer: (B)

12. A skater rotates through an angular displacement of magnitude $3\pi$ radians. How many revolutions is that?

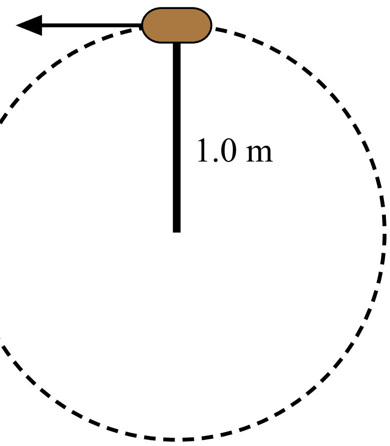
(A) 1/4
(B) 1/2
(C) 1
(D) 1.5
(E) 2
(F) 4

Answer: (D)

13. A skater rotates through an angular displacement of magnitude 3□ radians. How many degrees is that?

(A) 90 degrees
(B) 180 degrees
(C) 270 degrees
(D) 360 degrees
(E) 450 degrees
(F) 540 degrees

Answer: (F)




14. You are whirling a stone on the end of a string in a horizontal circle of radius 1.0 meter with an angular speed of 4.0 radians per second when the string breaks. Just after the string breaks, find the speed of the stone.

(A) 2.0 meters per second
(B) 4.0 meters per second
(C) 8.0 meters per second
(D) 16 meters per second

Answer: (B)

15. A discus thrower rotates twice around in a time of 3.0 seconds before releasing the discus. Find the frequency of the motion.

________________ Hz

Answer: 0.67 Hz

16. A tether ball is rotating around a pole with an angular speed of 3 radians per second. If the linear speed of the tether ball is 6 meters per second, find the radius of the ball's motion.

________________ meters

Answer: 2 meters

17. The mass of a women's hammer is 4 kilograms and the length of the wire is ~1.2 meters. Assuming the mass of the wire is negligible, find the rotational mass of the women's hammer.

_______________ $kg \cdot m^2$

Answer: 5.76 $kg \cdot m^2$

18. A heavy bowling ball has a mass of ~7 kilograms. Before it is released assume it is rotating at the end of an arm with a length of 1 meter. Find the rotational mass of the bowling ball (ignore the mass of the arm).

_______________ $kg \cdot m^2$

Answer: 7 $kg \cdot m^2$

19. A heavy bowling ball has a mass of ~7 kilograms. Before it is released assume it is rotating at the end of an arm with a length of 1 meter and that its speed when it is released is 9 meters per second. Find the angular speed of the bowling ball just before it was released.

_______________ radians per second

Answer: 9 radians per second

20. A heavy bowling ball has a mass of ~7 kilograms. Before it is released assume it is rotating at the end of an arm with a length of 1 meter and that the angular acceleration applied to the ball by the bowler is a constant 6 $rad/s^2$. Find the torque that the bowler applies to the ball. (Hint: use the result of problem 18 for the rotational mass.)

_______________ $N \cdot m$

Answer: 42 $N \cdot m$

21. The M16A2 rifle has a twist rate of 1 in 7 inches, a muzzle velocity of 3050 feet per second and a barrel length of 20 inches.

a. How many revolutions has the bullet made by the time it exits the rifle?

_______________ revolutions

Answer: 2.9 revolutions

b. How long does it take for the bullet to exit the rifle?

_______________ seconds

Answer: 0.00055 or $5.5x10^{-4}$ seconds

22. A diver does a complete rotation in half a second (0.5 s). Find the frequency of her motion.

_______________ Hz

Answer: 2 Hz

23. The mass of a women's hammer is 4 kilograms and the length of the wire is ~1.2 meters; 2 meters total including the arm length.

a. Assuming the mass of the wire and arm is negligible (?!), find the rotational mass of the arm/hammer combination.

_______________ $kg \cdot m^2$

b. Assuming the hammer is released at a speed of 10 meters per second, find the angular speed of the hammer just before the release.

_______________ radians per second

c. Assuming the hammer is released at a speed of 10 meters per second, find the angular momentum of the hammer just before the release.

_______________ $kg \cdot m^2 / s$

Answers: a. $16\ \mathrm{kg \cdot m^2}$
b. 5 radians per second
c. $80\ \mathrm{kg \cdot m^2/s}$

24. In 1986, at the European Championships, in Stuttgart, Germany, Yuri Sedykh from Russia set the world record in the hammer throw with a distance of 86.74 meters. (that record still stands today!) Before releasing the hammer, he turned around 3 times (3 or 4 is typical). The times of his revolutions were 0.44, 0.47, and 0.43 second.

a. Find Sedykh's average period.

________________ second

b. Find Sedykh's average frequency.

________________ Hertz

Answers: a. 0.45 second
b. 2.24 Hertz

# CHAPTER 8: Air and Water


Soccer star David Beckham

https://the-hollywood-gossip-res.cloudinary.com/iu/s--KoVqr7zB--/t_xlarge_l/cs_srgb,f_auto,fl_strip_profile.lossy,q_auto:420/v1368716495/david-beckham-on-the-pitch.jpg

VIDEO 8.1: David Beckham of England taking a free kick in a 2002 World Cup Qualifying match

https://digitalcommons.uri.edu/physicsofsports/59/

Select and watch VIDEO 8.1.

## 8.1: Air Resistance

David Beckham was already a world-famous soccer player before the movie "Bend it Like Beckham" came out in 2002 (a comedy featuring soccer but that had nothing to do with David Beckham directly). Part of his fame came from shots like the goal kick you just watched. That goal tied the match between England and Greece in 2001 and allowed England to qualify for the 2002 Soccer World Cup. Before discussing the physics Beckham used to make that very impressive shot, we need to learn a few things about objects traveling through the air. (By the way, can you think of any other sports projectiles that "bend" or "curve" like that soccer ball?)

One further note before we get started: a full-blown description of the interactions of fluids such as air and water with sports objects, or any objects, is quite complicated and would require discussions of boundary layers, turbulence, Reynolds numbers, and more. Here, we'll do the best we can with a simpler version of fluids and their effects and leave the more sophisticated aspects to another book and course.

Now select VIDEO 8.2 and let's jump off a cliff!

VIDEO 8.2: Cliff Jumping

https://digitalcommons.uri.edu/physicsofsports/60/

QUIZ 8.1

A moment after those cliff jumpers launched themselves off a cliff, which force that we have studied before did each one experience?

( x ) his/her weight
( ) friction
( ) tension
( ) the normal force

Before jumping, the cliff jumpers were more or less "at rest." After their leap, they were clearly moving, which means they were accelerating. Acceleration requires a force and that force as you hopefully selected correctly is gravity (weight). So the speed of each cliff jumper should increase from 0 to ~10 meters per second after the first second of "free fall," to ~20 meters per second after the next second, etc. Right? No. The velocity increase will actually not be as great as that.

In fact, if the cliff jumpers were to fall long enough (without hitting bottom) their velocity (and speed) would reach a constant value (~110 miles per hour). This is the meaning of **terminal velocity** (or **terminal speed**) which you have probably already heard of. It takes ~10 seconds in general for a person in free fall to reach terminal velocity. Let's look at a sketch of a falling object at terminal velocity based on what we have learned so far:

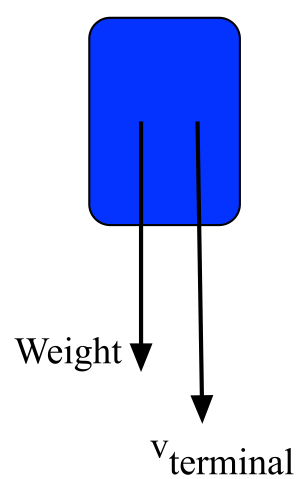



FIGURE 8.1: (Incomplete) Diagram of a falling object

I've shown the force on the object, the weight, and indicated the terminal velocity; both pointing down. What's wrong this picture?

QUIZ 8.2

First, if velocity is constant what can we say about the acceleration?

| | |
|---|---|
| (   ) | The acceleration is increasing. |
| (   ) | The acceleration is decreasing. |
| (   ) | The acceleration is constant but not zero. |
| ( x ) | The acceleration is zero. |

This goes back to the first chapter. If the velocity is constant, the acceleration is zero. Now, if the only force acting on the object is the weight, then what?

QUIZ 8.3

If the only force acting on the object is the weight:

| | |
|---|---|
| (   ) | Not a problem; the weight causes the terminal velocity. |
| ( x ) | Problem: if the acceleration is 0, there must be at least one other force to cancel the weight. |

For an object at its terminal velocity, the acceleration is zero, so there must be at least one other force besides the weight acting in the other direction. That force is the force of the air hitting the object as it falls; or we can think of it as the reaction force to the force the object exerts on the air to push it out of the way. We call this force **air resistance** or **air drag** or the **drag force**. So a more correct picture of a falling object looks like this:

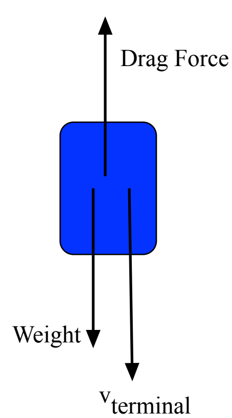



FIGURE 8.2: (More Correct) Diagram of a falling object

I think of the air as composed of many, many atoms and molecules (which it is) and the drag force as the force of all these atoms and molecules colliding with an object as it travels through the air. The direction of this force will always be in the opposite direction from the direction of motion ("up" for the cliff jumpers).

The drag force turns out to depend on several important parameters. The first of these is the velocity (or speed). When the cliff jumpers first jumped off the cliff, their velocity was zero and the only force was their weight (the drag force was zero initially). As their velocity increased, the drag force increased until it became equal to the weight (in magnitude), assuming that their fall lasted long enough. So apparently the drag force depends on the speed. When the jumpers reached their terminal speed the two forces cancelled, the acceleration went to zero, and the velocity remained constant at the terminal velocity. For most sports objects in normal situations, the drag force is proportional to the square of the velocity (it can be directly proportional to the velocity under some conditions).

QUIZ 8.4

Assume the drag force on an object is 2 Newtons when the object has a speed of 5 m/s. If the speed increases to 10 m/s, what will be the new drag force?

____________ Newtons

(Answer: 8 Newtons)

Because the drag force is proportional to the square of the speed, doubling the speed causes the drag force to increase by a factor of 4.

## 8.2: Air Resistance 2

What else does the drag force depend on? Several things actually. To get some more ideas, select VIDEO 8.3 and we'll watch a dramatic sky diving rescue. In 1987 near Coolidge, Arizona, sky diver Debbie Williams collided with a fellow diver during a jump and was knocked unconscious. Gregory Robertson read the situation correctly and was able to get to Debbie and open her parachute ~10 seconds before impact with the ground. Pay special attention to the initial actions of Greg in his rescue attempt.

VIDEO 8.3: Sky Diving Rescue

https://digitalcommons.uri.edu/physicsofsports/61/

Pretty amazing even though I believe this video is a reenactment taken from an episode of the TV show, "Rescue 911." (Debbie suffered a number of serious injuries as a result of her adventure, but she did survive. Greg was later granted an entry in the "Guinness Book of World Records" for the "lowest midair rescue.")

The point of watching this rescue was to observe and interpret the method by which Greg caught up to Debbie. Debbie was falling in a more-or-less spread-eagle configuration, arms and legs extended. To catch her, Greg tilted his body forward so that he had his head down. As a result, he speeded up and was able to catch her in time to pull her parachute cord. What is the physics behind this action and how does it relate to the drag force?

QUIZ 8.5

By tilting forward into a head-down configuration, what did Greg change that caused him to speed up?

( ) his mass
( ) his weight
( x ) the area of his body he exposed to the air in his direction of travel

That was a pretty loaded question. Hopefully you could see from the video that by reducing his cross-sectional area in the direction of travel he reduced the drag force so he could increase his acceleration. So apparently the drag force of air is related to the cross-sectional area; it is and in fact it is directly proportional to this area. Let's follow that up with the diagram below:

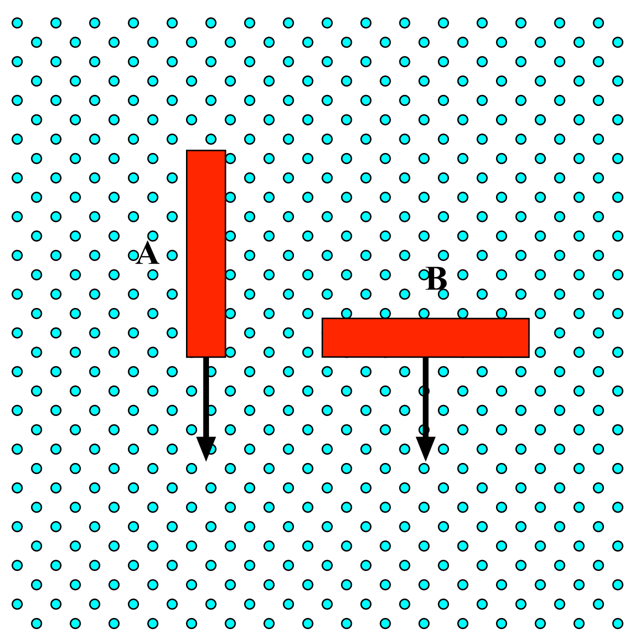



FIGURE 8.3: Sketch of two falling objects

QUIZ 8.6

The two falling objects shown above are supposed to be identical except for their orientations. Which object would encounter greater drag force?

( ) object A
( x ) object B

I hope that the figure above helps to clarify why the drag force increases with cross-sectional area. One way to think of it is that with a greater area, more atoms and molecules get hit and must be pushed aside. This obviously accounts for the benefit of deploying a parachute on the way down. Let's assume, for example, that the cross-sectional area of the parachute is 20 times the cross-sectional area of a sky diver. Then the drag force of a sky diver with the parachute open will be ~20 times the drag force on the sky diver with parachute closed.

Now let's apply what we have learned so far about the drag force to other sports and sports objects. The drag force does not require that the object be falling. Obviously any sports object, whether person, vehicle, or projectile travels through the air so all will experience some degree of drag force. (We'll consider a different situation in Chapter 10.) The drag force will in all cases be directly proportional to the area and also to some function of the velocity (generally the square of the velocity as we have already discussed.)

Let's consider cycling next. If you remember or look back at the cycling videos we watched in Chapter 7, you will notice that the riders are very "hunched over" on their bikes. Why? The answer now should be clear - hunching over reduces the cross-sectional area exposed to the oncoming air so it reduces the drag force (by as much as ~30%).

Let's compare cycling to running. Assume that the bicycle riders are not actually hunched over but are fairly erect on their bikes. Which racer will experience the greater drag force, a runner or a cyclist?

QUIZ 8.7

Assuming their cross-sectional areas are about the same, which racer will experience the greater drag force, a runner or a cyclist? Hint: think about what we learned about air resistance in the first section of this chapter.

( ) The drag forces should be about the same.
( ) The drag force on the runner should be greater.
( x ) The drag force on the cyclist should be greater.

In the previous section, we learned that the drag force depends on the velocity. Since in a race the speed of the cyclist is greater than the runner, the drag force on a cyclist will also be greater. In fact, a cyclist riding at relatively high speed (>25 miles per hour) needs most (~90%) of his or her power just to overcome the drag force. For runners this power expenditure due to air drag is ~10%.

Speaking of cycling, we can now understand the physics behind "drafting", when one cyclist rides behind but very close to another cyclist. (This practice is in fact illegal in the cycling portions of some triathlons.) The forward cyclist blocks some of the air so the trailing cyclist(s) experiences a reduced drag force, saving ~30% of his or her energy. "Motorpacing" involves a cyclist riding behind a car or motorcycle, allowing for incredible speeds. Using this technique, in 1985 a speed record for a cyclist was set by John Howard, a former Olympic cyclist. He attained a speed of over 152 miles per hour riding a specially designed bicycle. (Don't try this at home!)

In speed skating, drafting can play an important role as well. It has been estimated that ~80% of the energy expended by the skater is used to overcome air drag. When speed skaters skate and work as a team, rotating the front skater so the others can draft, then each skater expends ~3/4 of the power that would be expended by a solo skater.

QUIZ 8.8

The cross-sectional areas of a shot and a baseball are similar (How close are they? Check it out). Which projectile will experience the greater drag force, a world class shot put vs. a home run baseball? (Assume the size of the two projectiles are similar.)

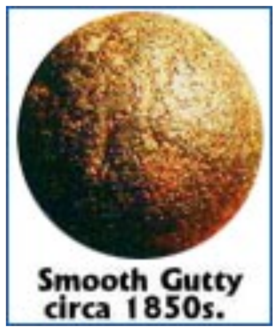
( ) The drag forces should be about the same.
( ) The drag force on the shot will be greater.
( x ) The drag force on the baseball will be greater.

The speed of a baseball hit for a home run (~110 miles per hour initially) is considerably greater than that of a world class put (~30 miles per hour) so for the same reason as for cyclist vs. runner, the drag force on the baseball will be greater than that on the shot. A put of 70 feet will be reduced by ~1/2 foot due to the drag force. In contrast, a well-hit baseball that would travel ~750 feet in vacuum will only travel ~400 feet through the air! Can you think of other sports projectiles that would be significantly influenced by the drag force?

As you can probably imagine, wind can play a significant role in the behavior of many sports objects with a dependence on both wind speed and wind direction. We'll leave that subject alone in this book.

## 8.3: Air Resistance 3

Are we done with the drag force and the factors that affect it? No, not yet. Lets' talk about golf next. Early golf balls from ~1850 (but not the earliest ones; those were first wooden then were later made of leather stuffed with feathers) were round, smooth spherical balls molded from natural rubber (see Figure 8.4 below). These balls did not travel particularly far and a good drive was less than 150 yards. It was found that when the balls were older and roughened up the balls would travel significantly further. Now golf balls are "roughened" intentionally by the manufacturers. What is the form of this "roughening?" Yes - the dimples on all golf balls, as shown below. There is a lot of money in golf so a lot of money has been spent to perfect this dimpling - how many dimples, what shape, ...? Now a well-hit dimpled golf ball will travel ~75% further than an equivalent smooth ball.




http://www.golfballmuseum.co.uk/ishop/images/818/4gutty_1.jpg

FIGURE 8.4: Early rubber golf ball

FIGURE 8.5: Modern golf ball
https://media.istockphoto.com/photos/white-golf-ball-picture-id898398664?k=6&m=898398664&s=612x612&w=0&h=OZHOYS-3g3BDEupZUoYn6g0Ez0tmgoInJkbzBa1pUpU=

But why does roughening a golf ball make it travel further? It seems at first to be counterintuitive. Of course, too much roughening is not going to increase the travel distance - there are limits (but what are those limits?) The physics behind this effect involves a discussion of boundary layers and turbulence, which we will leave for your research or discussion elsewhere. We will just accept for now that a certain degree of roughness on some sports objects such as golf balls will make them travel further.

Baseball: looking at a typical baseball shown below, we can see that there is some "roughness" due to the raised stitch pattern on the ball. The roughness from these stitches can add ~50 feet compared to a (smooth) ball that was hit ~350 feet. That's significant. Can you think of any other sports in which the smoothness or roughness of a ball or other sports object might have important consequences? (Check out the ban of javelin tail-roughening in 1991 for example.)

FIGURE 8.6: Modern baseball

https://media.istockphoto.com/photos/baseball-on-white-picture-id529982024?k=6&m=529982024&s=612x612&w=0&h=7HTHWWZoKRl1fPIFql-v3pR4aClE6WbFb6GnfoB9jbo=

The fact that roughness affects the flight of a baseball is one reason that pitchers are not allowed to intentionally scuff up a ball and the reason that umpires will often swap out a ball after it hits the dirt during a pitch. (Take a guess as to how many baseballs are used in a Major League game: ~60-70!) In addition, the "roughness" caused by the stitching accounts for the way a knuckleball "dances" around and is hard to hit even though it is not pitched with very great speed. As the knuckleball makes its way to the plate, different faces of the baseball with more or less stitches slowly rotate around to the direction in which the ball is thrown.

Now I have another air resistance question: Consider a falling object with some amount of drag force on it due to collisions with the atoms and molecules in the air, as we have considered above (A in the diagram below). Now what if the same object falls through "less air", by which I mean that the density of air is less (B below). Is anything different?

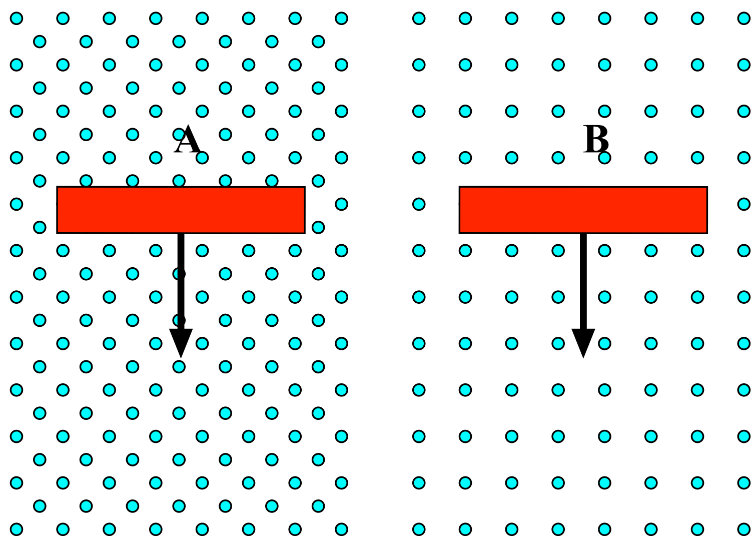



FIGURE 8.7: Sketch of two objects in free fall

QUIZ 8.9

What can we say about the drag force on identical objects for a "normal" density of air (A) vs. for a reduced air density (B)?

( ) The drag force is the same for both.
( x ) The drag force is greater for A.
( ) The drag force is greater for B.

Hopefully you selected correctly. I think it makes sense: less air = less drag force. In fact, the drag force due to air is <u>proportional to the density of the air</u>. Now are there any realistic conditions in which the air density would be different in various sports situations. Yes, is the answer. The *elevation* of sports stadiums and arenas does vary enough to have a noticeable effect in some cases.

For example, the density of air in Denver, Colorado (the home of the Colorado Rockies professional baseball team and the Denver Broncos professional football team among others) at an elevation of ~1 mile is approximately 17% less than the density of air at sea level. The density in Mexico City (where the Olympic Games were held in 1968) at an elevation of 7800 feet is approximately 25% less than the density at sea level.

QUIZ 8.10

If hit identically, where will a baseball or golf ball travel further?

( ) At sea level
( x ) In Denver
( ) No difference

Because of the change in air density, it has been estimated that a baseball hit 400 feet at sea level would travel ~420 feet in Denver, making Coors Field (home of the Rockies) a real "hitter's ballpark." Likewise, a 300 yard drive in golf at sea level would travel ~330 yards in Denver. (Notice that we are talking in feet for baseball but yards for golf - why the big difference?) We'll discuss this later in the chapter.

Even the results of a simple running race can be affected by lower air density. It has been estimated that a runner could achieve a speed ~2% greater racing in Mexico City than at sea level. And this will affect other track and field events. For example, consider a faster approach in the pole vault competition held at higher elevation and reduced air density. What would happen?

QUIZ 8.11

If the air density is lower so the approach is faster, how will the maximum height obtained in pole vaulting be affected?

( x ) The maximum height would be greater.
( ) The maximum height would be less.
( ) The maximum height would be the same.

Relating this to energy considerations, lower air density leads to a faster approach. That results in greater kinetic energy of the vaulter which will lead to greater gravitational potential energy and a higher vault. (And less air resistance while the vaulter is in the air as well.)

In fact, in the 1968 Olympics held in Mexico City, men set world records in the 100, 200, 400, and 800 meter races as well as the long jump, the pole vault, and the triple jump. (Of course, athletes would have to train well enough to be acclimated to these different conditions.) Similarly, all men's and women's long-track speed skating world records at all distances have been set when the events were held at relatively high elevations, mostly at Calgary with an altitude of 3400 feet or at Salt Lake City (4300 feet). Can you think of any other sports that might be affected like this?

Temperature and humidity also have an effect on the air density and will also influence the sports situations we just discussed. Can you think of why and how?

Another question: Let's get back to sky diving. If the air density was lower due to an increase in elevation, how would the terminal velocity of a sky diver be affected?

QUIZ 8.12

If the air density were lower due to an increase in elevation, how would the terminal velocity of a sky diver be affected?

( x ) The terminal velocity would be greater.
(   ) The terminal velocity would be less.
(   ) The terminal velocity would be the same.

Again, less air means less drag force so the velocity must be greater for the drag force to equal the weight of the sky diver. In 1960, Air Force Captain Joseph Kittinger jumped from a balloon at a height of 102,000 feet. He was able to free fall for 4.5 minutes and achieve a terminal velocity somewhere in the range of 614-702 miles per hour! (That's close to the speed of sound at ~740 mph.)

One final issue involving air resistance: We have already learned that the drag force will reduce the horizontal travel distance (often called the "range") of a sports projectile such as a baseball or a golf ball. Will it also affect the height and shape of the trajectory?

In Chapter 2, we digitized the trajectory of a basketball and found that the path is quite symmetric in a shape called a parabola. I include my digitized trajectory from Chapter 2 in the figure below:

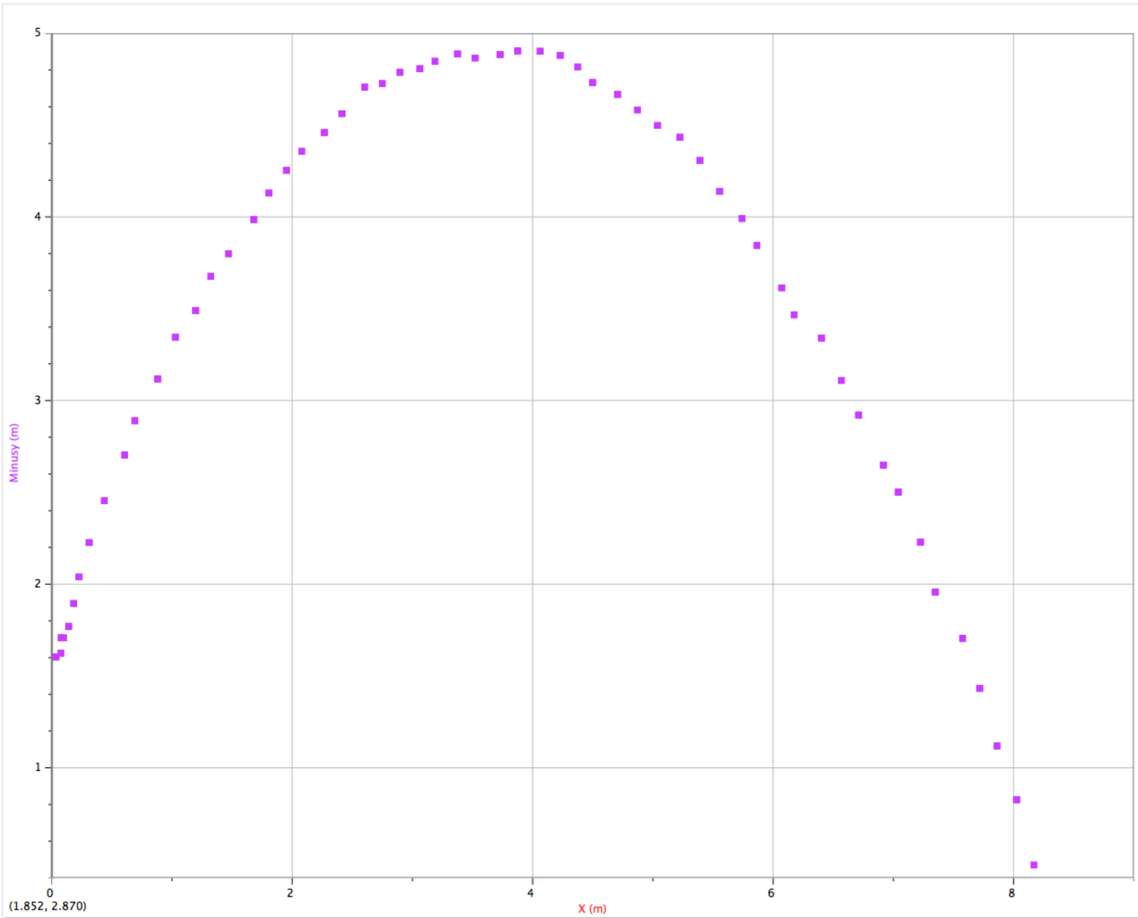
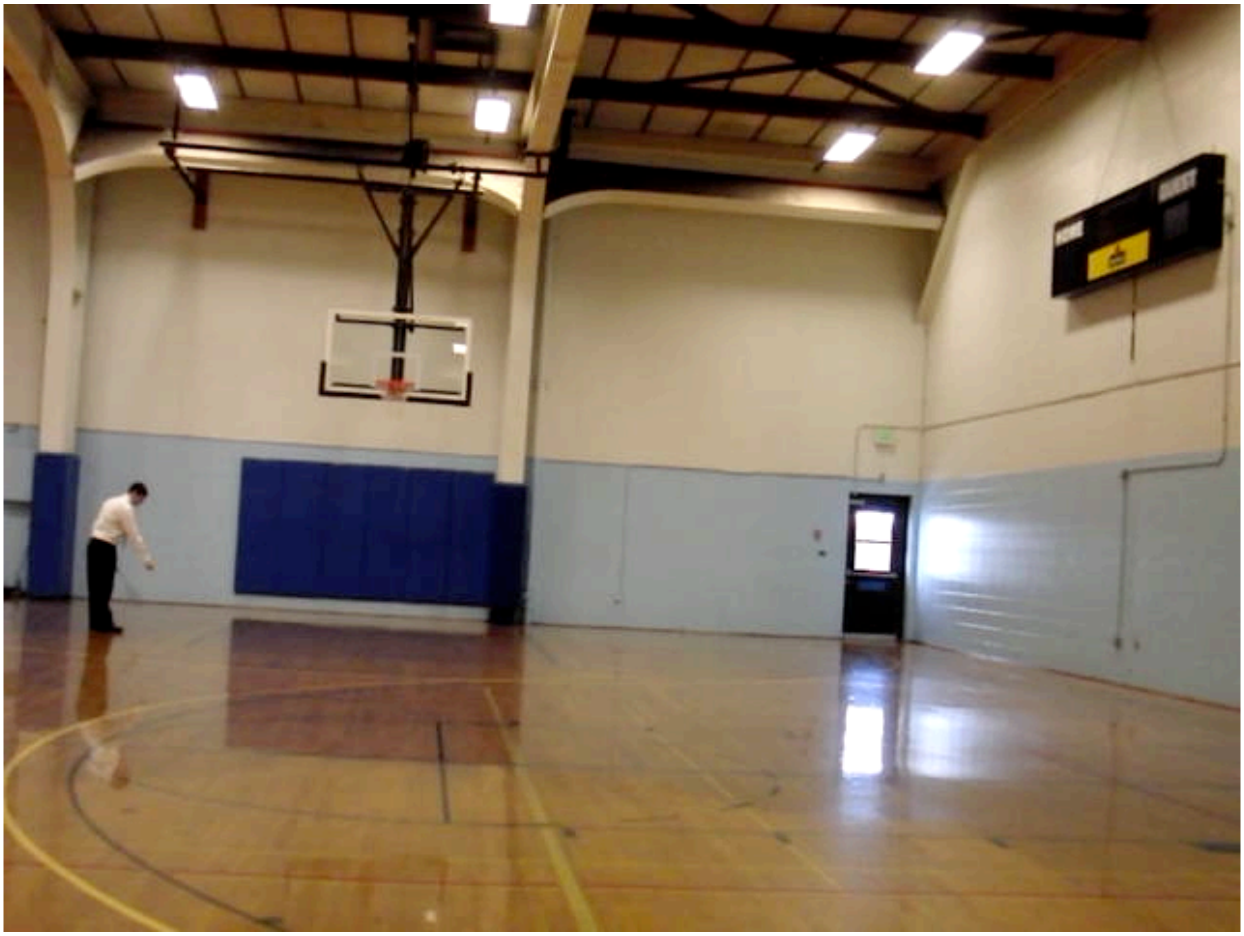



FIGURE 8.8: Trajectory of a thrown basketball

We also learned earlier in this chapter that air resistance does not have much of an effect on the range of a shot put (~0.5 foot reduction out of 70 feet). Let's now look at a projectile that I expect would be much more affected by air resistance - the badminton shuttlecock (wouldn't you agree?).

Now select VIDEO 8.4 and watch a shuttlecock in flight. Then we'll digitize the trajectory as in earlier chapters.



VIDEO 8.4: Shuttlecock in flight

https://digitalcommons.uri.edu/physicsofsports/62/

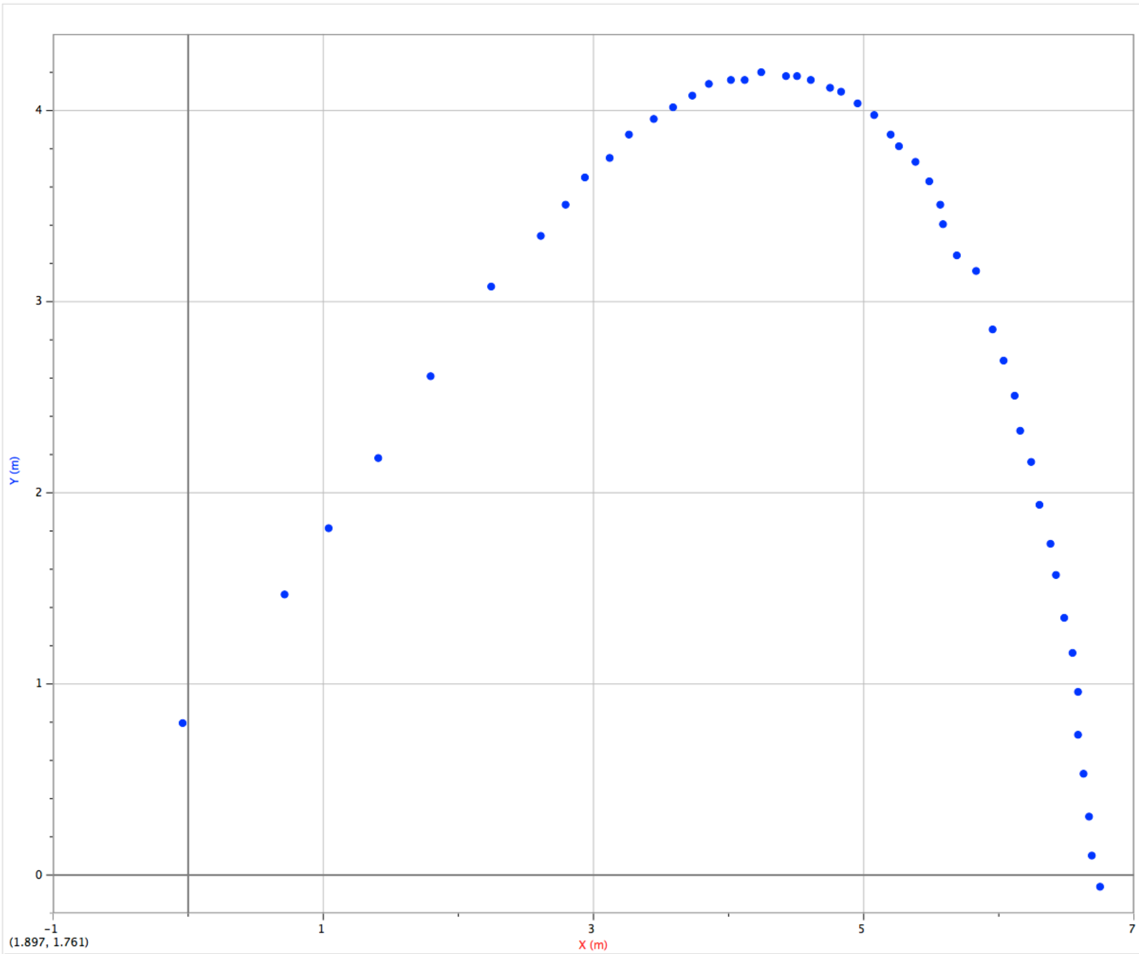


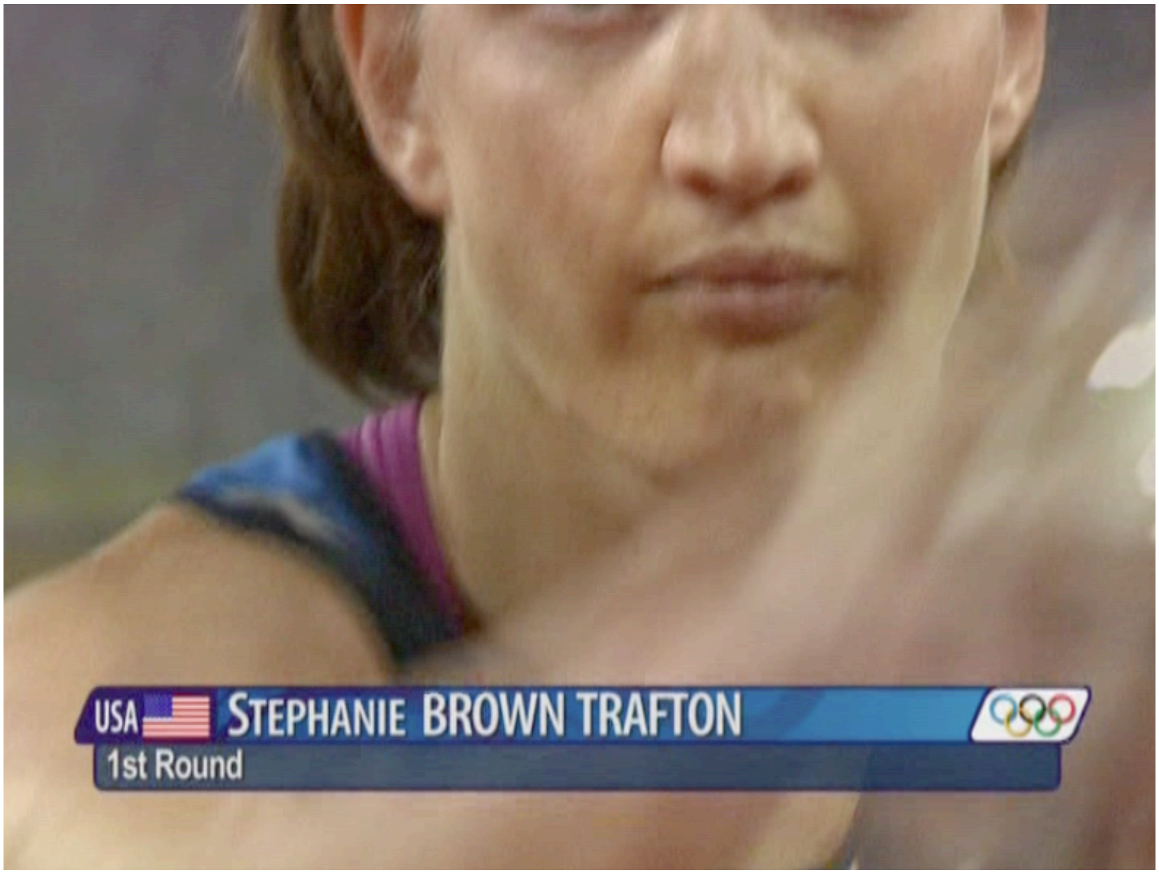

FIGURE 8.9: Author's digitization of the trajectory of a shuttlecock

Without doing any further analysis or curve fitting I think you can see that the path of the shuttlecock is not symmetric and does not follow a parabola like the shot put. Air resistance acts both in the vertical and horizontal directions so we should expect that both the range and the maximum height should be affected. In addition, since the acceleration from the drag force is not constant (it depends on the velocity) the shape of the curve is affected as well. One real consequence of this in some sports situations is that due to air resistance the optimum launch angle (to achieve the maximum range) will no longer be 45°. Can you find any evidence of this in various sports?

To summarize, the drag force due to air resistance is proportional to the cross-sectional area and the density of the air and is proportional to the square of the speed (under many conditions).

## 8.4: Lift

Now we are going to take a look at a discus throw. Of course, the discus must be subject to at least some drag force, but is that the only other force (besides the weight?). Select VIDEO 8.5 and watch a throw at the 2008 Olympic Games by Stephanie Brown Trafton of the United States. She went on to win the gold medal in this event with a throw of 64.74 meters.




VIDEO 8.5: Discus throw by Stephanie Brown of the U.S. in the finals of the 2008 Olympics

https://digitalcommons.uri.edu/physicsofsports/63/

Let's compare the discus to the shot put. The discus used by women in the Olympics has a mass of 1 kilogram (2 kilograms for the men). The women's shot has a mass of 4 kilograms (7.26 kilograms for men).

QUIZ 8.13

For which event at the 2008 Olympics would you expect the gold medal throwing distance (range) to be greater?

( ) the shot put
( x ) the discus
( ) about the same

Considering the mass of women's shot is four times the mass of the discus, I would have been quite surprised if the shot put would beat out a discus throw. But maybe you would be surprised to learn that 2008 Olympics gold medal women's shot put (Valerie Vili of New Zealand) was less than 1/3 the distance of Stephanie's winning throw (20.56 meters vs. 64.74 meters). There's a (physics) reason for this big difference and it has to do with another property of air interacting with flying objects.

To understand this effect, let's first consider a different disk-shaped flying sports object, the frisbee.

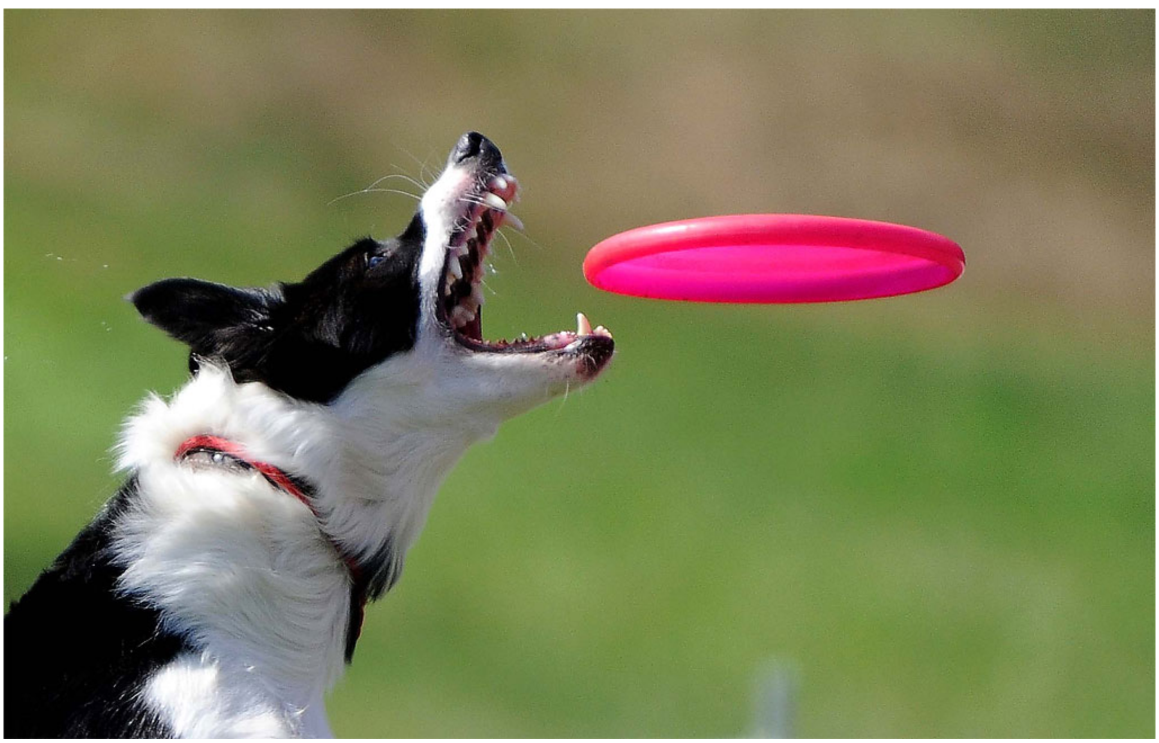


FIGURE 8.10: Frisbee in flight

http://designyoutrust.com/wp-content/uploads/2011/08/potd6.jpg

With a good throw a frisbee will coast along in a fairly horizontal trajectory for a significant distance, obviously not a parabola. What is keeping it from falling to the ground? There must be some other force in play, a **lift force**. To understand this better I provide below a sketch of a frisbee moving more or less horizontally through the air from left to right.

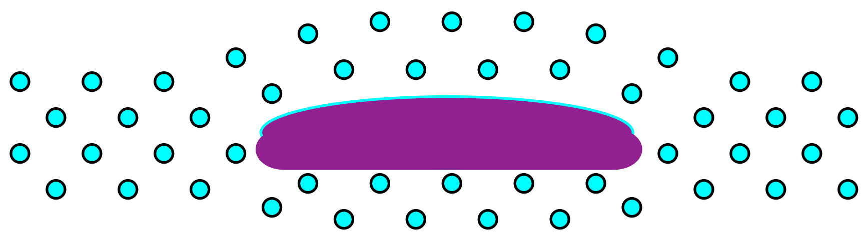


FIGURE 8.11: Sketch of a frisbee in flight

Notice that because of the slightly domed shape of the frisbee, the air particles must travel a greater distance over the top of the frisbee than along the bottom. If the air particles that were near each other before encountering the front of the frisbee are to meet at the back end (which they do - that's a "boundary layer" issue), that means that the air must travel <u>faster</u> over the top of the frisbee in order to cover the greater distance.

That's when **Bernoulli's Principle** comes into play. He discovered that "when the speed of a fluid increases, the pressure of the fluid decreases." Since pressure is force per unit area, greater speed in a fluid leads to a reduced force. A simple illustration of this that you can try: lightly holding a piece of paper horizontally, blow over the top surface of the paper. You should see the paper rise due to Bernoulli's Principle. What about the frisbee then?

QUIZ 8.14

Due to Bernoulli's Principle, where will the vertical force on the frisbee be greater?

( ) on the top
( x ) on the bottom
( ) about the same

Lower speed along the bottom of the frisbee means a greater force on the bottom than on the top. Therefore, the net force on the frisbee due to the air is directed upwards. This is a lift force. This force partially counteracts the force of gravity, allowing the frisbee to remain in flight longer with a relatively flat trajectory. Similar to the drag force, the lift force due to the Bernoulli effect is proportional to the density of the air and to the square of the speed.

As another example, below I show a sketch of the wing of an airplane from the side. Definitely curved and a lift force is at work. Can you think of any other flying objects that have curved wings (or blades!) of some kind? Another example is the curved sail on a sailboat. In this case the lift is not vertical but rather horizontal, propelling the boat along the surface of the water.

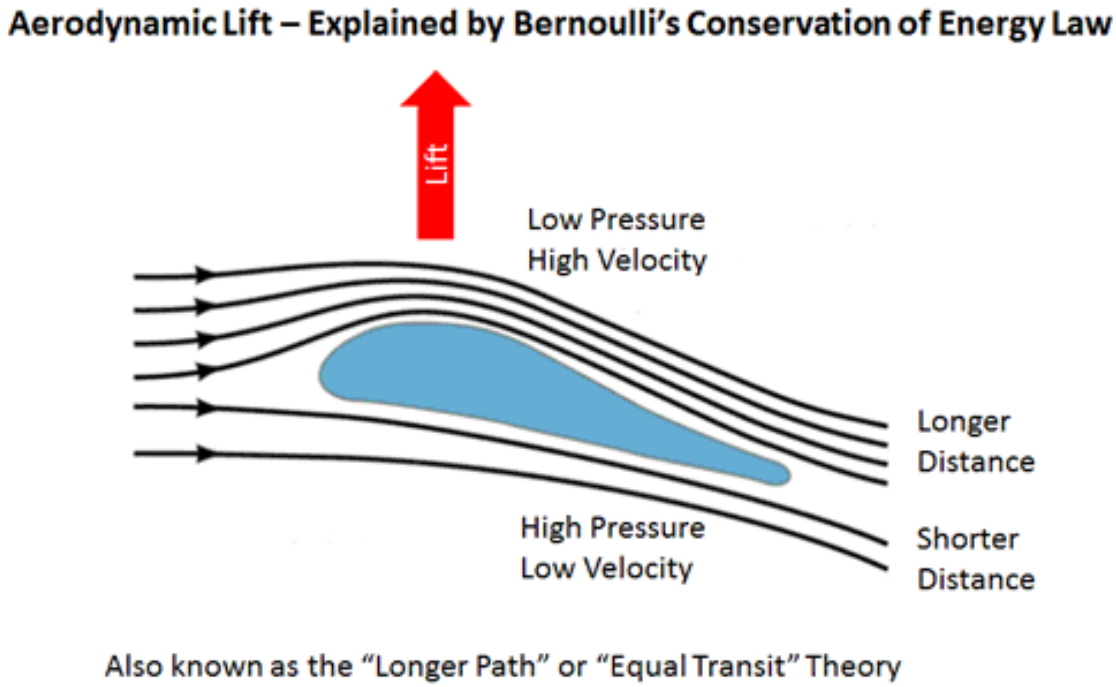



FIGURE 8.12: Sketch of an airplane wing in flight

https://www.mpoweruk.com/images/Lift%20by%20Bernoulli.gif

Finally, some high performance automobiles have "Automotive wings" (not the same as "spoilers" - what's different?) as in the figure below. These are configured as upside-down wings. (Why upside down?)

FIGURE 8.13: Super race car with an automotive wing

https://previews.123rf.com/images/deusexlupus/deusexlupus1711/deusexlupus171100155/89914106-shiny-midnight-black-modern-super-race-car-rear-wing-shot.jpg

FIGURE 8.14: Two examples of a discus

http://photos.demandstudios.com/getty/article/146/252/200443171-001_XS.jpg

Back to the discus. The discus is actually symmetric so there is no path length and speed difference for air flowing over the top and bottom. Bernoulli's Principle will therefore not provide any lift for a discus traveling in a horizontal direction. However, if the discus is titled upward at some angle (but not too much) it will receive a lift force from the greater amount of air hitting the bottom of the discus vs. the top (I think of more collisions with air particles on the bottom). This is illustrated by the image of a discus in a wind tunnel experiment shown below. If you observe carefully, you can see in the discus video you watched earlier that the discus is inclined at some angle throughout its trajectory. You also might correctly imagine that the flight of the discus is significantly affected by wind conditions.

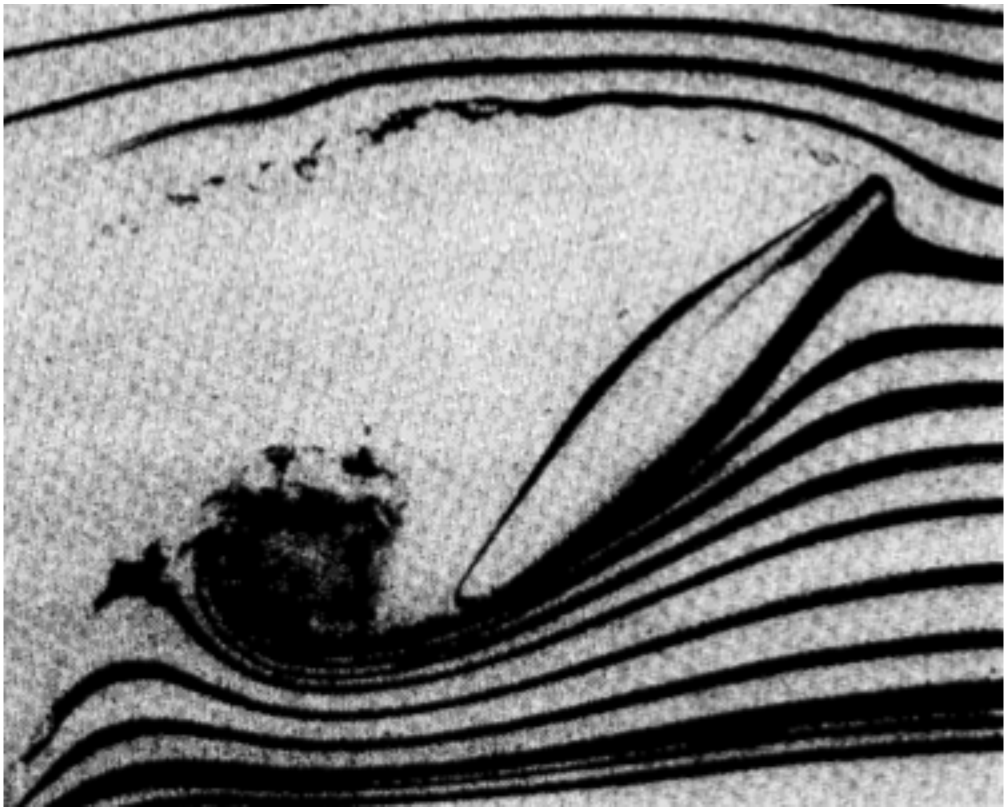


FIGURE 8.15: Discus in a wind tunnel

http://scitation.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=AJPIAS00004900 0012001125000001&idtype=cvips&doi=10.1119/1.12560&prog=normal

## 8.5: Spin

We are finally close to having enough information to understand the physics behind the dramatic curving goal by Beckham that we watched at the beginning of the chapter. To get to this we're first going to look at a drive off the tee in golf. The ball is subject to at least some drag force, but is that it - the only other force (besides the weight)? Select VIDEO 8.6 and watch Tiger Woods make a hole-in-one in 1996 at his first PGA Tour event as a professional (he went on to finish tied for 60th place in the tournament).


VIDEO 8.6: Tiger Woods making a golf shot

https://digitalcommons.uri.edu/physicsofsports/64/

Now this shot traveled "only" ~190 yards; but if necessary, golfers routinely can hit drives of 300 yards or more. That's quite a distance. How do they do it? These shots benefit from another kind of lift that we are going to examine now, one involving the spin of the golf ball in flight. To see where the spin comes from, select VIDEO 8.7 and watch again the slow motion video of a golf club hitting a golf ball that we first saw in Chapter 6. Observe the spinning of the golf ball.


VIDEO 8.7: Golf ball being struck by a golf club

https://digitalcommons.uri.edu/physicsofsports/65/

Hopefully you noticed the tilted face of the golf club, probably ~10º. As the ball rolls up this tilted face, it will start to spin. I could just see the ball start to rotate by the end of the video. Did you catch that? A well-struck golf ball can obtain a spinning rate of ~4000 revolutions per minute. This "backspin" will keep the ball in the air up to a few seconds longer and result in an increase in the driving distance between 60 and 100 yards - that's a lot! How does that work? Below I sketch a side view of a golf ball traveling from left to right with backspin. I also sketched in a few air particles that are more or less "stuck" to the ball. This is called the "boundary layer" - which I couldn't avoid mentioning (again!).

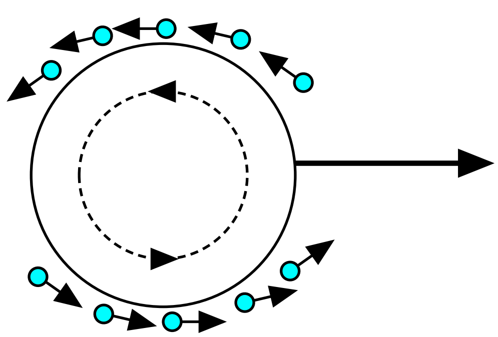


FIGURE 8.16: Sketch of spinning golf ball in flight

The important point is that because of the backspin the air particles near the top of the ball have some speed in the opposite direction from the direction of the ball's travel. In contrast, the air particles at the bottom have some additional speed due to the spin in the same direction as the ball's travel direction. This means that the air particles at the top of the ball are traveling with *greater* speed than the air particles at the bottom.

Can you see why the speed is greater for the air on the top? Consider this analogy: Imagine that a passenger is standing in the car of a train that is moving forward along the tracks, as shown below. Then the passenger decides to run along the car in the same direction that the train is traveling (A). Later, the passenger turns around and runs in the opposite direction (B). What about the speeds of the passenger with respect to the train? What do you come up with?

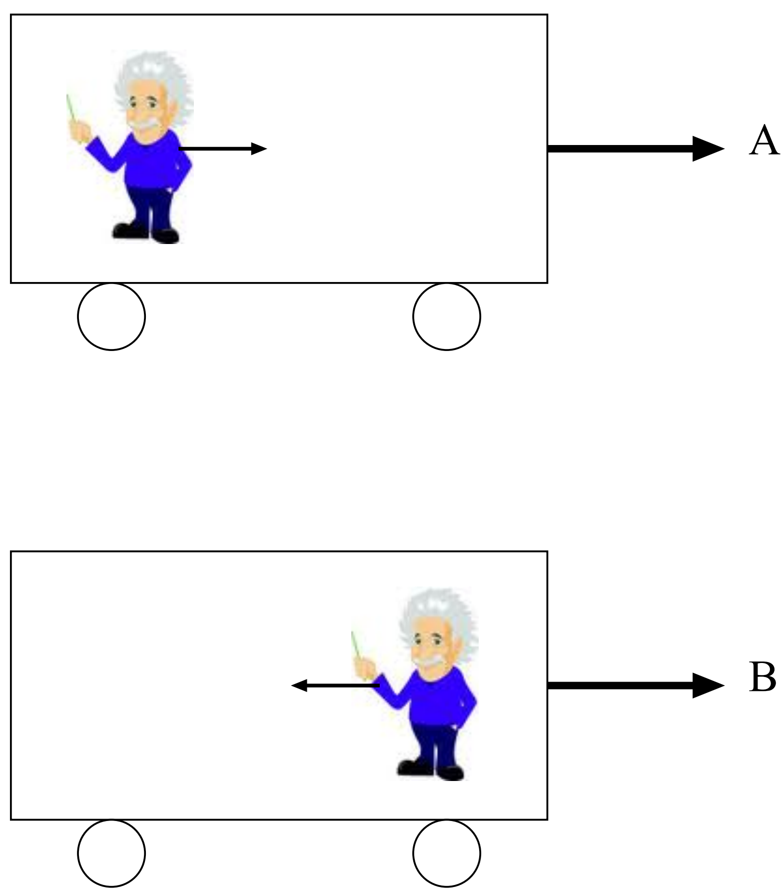



FIGURE 8.17: Sketches of a passenger moving on a train

http://t0.gstatic.com/images?q=tbn:ANd9GcTDaLpfmVriTVBWn5YAsVi4Cxi82cgCtUq
AEz2r6_HnyM7OTO1PWA

QUIZ 8.15

What about the speed of the passenger vs. the speed of the train in the cases shown above?

( ) Speed of passenger in A is greater than speed in B.
( x ) Speed of passenger in B is greater than speed in A.
( ) Speed of passenger in B is the same as speed in A.

Hopefully you selected correctly. For the passenger running in a direction opposite the direction of travel for the train, the speeds add together so his total speed will be greater. This applies to the air particles traveling around in the same direction as the spinning golf ball. The air on the top will have greater speed with respect to the ball than the air at the bottom.

That still doesn't explain why the golf ball with backspin gets some lift. We need to add what we have learned from Bernoulli in the previous section. According to his principle, if the speed of a fluid is greater, the pressure is less. Applying this to the spinning golf ball, the air on the top is traveling with a greater speed than the air on the bottom. Therefore, the air pressure and the force on the ball is less on the top than on the bottom. So there is a net force from bottom to top, resulting in a lift force on the ball in the upwards direction. This combination of Bernoulli's Principle combined with spinning object is called the **Magnus Effect** or **Magnus Force**. Similar to other forces we have studied in this chapter, the Magnus Force is proportional to the density of the fluid, the cross-sectional area of the projectile, the speed of the projectile, and now the spin rate of the projectile.

QUIZ 8.16

If the Magnus Force on a golf ball spinning at a rate of 2000 revolutions per minute is 0.10 Newtons (approximately 1/4 of the weight of a golf ball), what will be the Magnus Force if the ball is spinning at 3000 revolutions per minute?

____________ Newtons

(Answer: 0.15 Newtons)

Another ball that can obtain some lift from backspin and the Magnus Force is the baseball. If you carefully watch a long fly ball or home run you might notice that the bat often strikes the ball on the lower portion of the ball which will induce some backspin, possibly as much as ~2000 revolutions per minute. It has been estimated that the Magnus Effect can add 10-20 feet to the range of a well-hit baseball traveling ~400 feet in total. Not as significant as for golf, but this could be the difference between a home run and a deep fly out.


FIGURE 8.18: Soccer star David Beckham

https://the-hollywood-gossip-res.cloudinary.com/iu/s--KoVqr7zB--/t_xlarge_l/cs_srgb,f_auto,fl_strip_profile.lossy,q_auto:420/v1368716495/david-beckham-on-the-pitch.jpg

The Magnus Effect does not always result in a lifting force. If the golf ball in Figure 8.15 was instead hit such that the ball rotated in the opposite direction we would call that topspin. The golf ball in that case would feel a Magnus Force that was directed downwards which would cause the ball to remain in the air for a shorter time and to travel a shorter distance than the ball struck with no spin. (This is usually not a desirable outcome in golf!). Can you think of a sport in which a topspin shot is a good offensive shot (think "topspin lob")?

If instead a ball was struck from the side, then a sideways Magnus Force would result. In golf (again not desirable) this would be a "hook" shot or a "slice" (which is which?). In other sports, this sideways Magnus Force is the intention. Let's see what would happen in a particular situation.

QUIZ 8.17

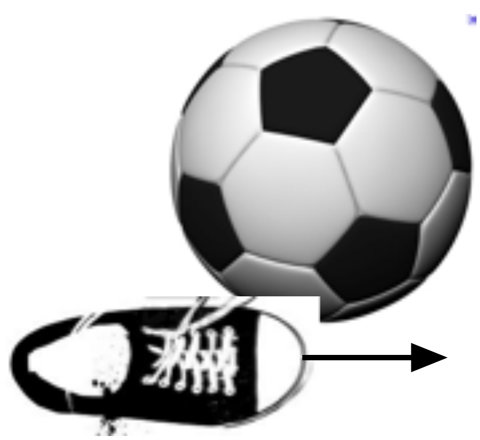


FIGURE 8.19: Schematic of shoe kicking a soccer ball

http://us.123rf.com/400wm/400/400/fet/fet1005/fet100500034/6989951-athletic-shoes-sneakers.jpg

http://cdn.shopify.com/s/files/1/0257/6087/products/755957ca0e8d95bb1d4e9ac2c8083de9.png?v=1539833096

A. A soccer ball is kicked on the right side of the ball, as shown. Which way will the ball start to spin as viewed from above?

( ) clockwise
( x ) counterclockwise

B. With the ball spinning counterclockwise, in which direction will the Magnus Force act?

( x ) to the left (away from the side of the kicker's foot)
( ) to the right (towards the side of the kicker's foot)

This situation is really very similar to the golf shot we discussed earlier. In this soccer ball example, the counterclockwise rotation of the ball will cause the air near the ball to have a greater speed on the left side (away from the kicker's foot) than the air on the right side. This will make the air pressure less on the left side which will result in a net force directed from right to left, perpendicular to the direction of travel. This will cause the ball to accelerate to the left which will cause the ball to curve to the left, just like Beckham's famous goal. That's it! That's what "bending it like Beckham" is all about (the physics anyway).

FIGURE 8.20: Brandon Claussen of the Cincinnati Reds pitching a baseball

http://upload.wikimedia.org/wikipedia/commons/thumb/2/25/Baseball_pitching_motion_2004.jpg/420px-Baseball_pitching_motion_2004.jpg

One last example: the curve ball in baseball. Even the fastball is thrown with spin (only the knuckleball has almost no spin, as discussed previously) but it is the "breaking balls" (curveball, slider, screwball) for which the pitcher intentionally pitches the ball with spin in various directions to make the baseball curve in some way in order to confuse the batter. Each of these pitches makes use of the Magnus Effect in much the same way as we have already discussed for the golf ball and the soccer ball. The baseball does not stay in the air for very long between pitcher's mound and batter's box, so you should not expect the deviation due to the Magnus Force to be substantial, only about one foot or so.

So does that mean that a pitched curveball will curve by ~1 foot so it will end up one foot lower than it was thrown? Not quite. Let's look a sketch of the pitching/batting situation:

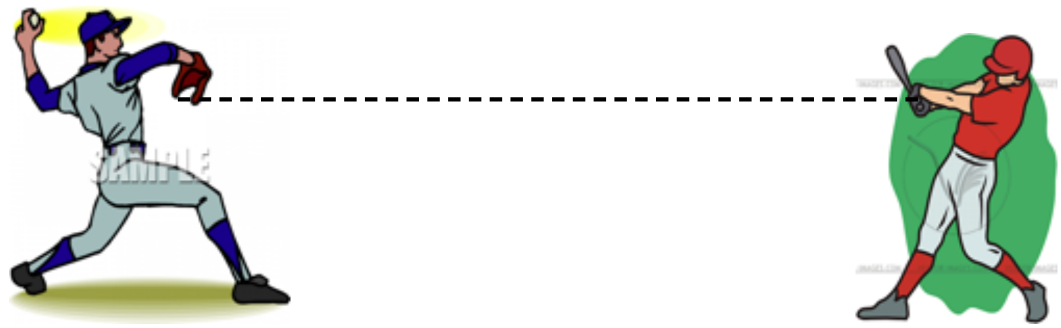



FIGURE 8.21: Schematic of pitcher pitching to a batter

http://www.theclipartdirectory.com/clipart/Baseball/baseball_pitcher_139751_tnb.png

??????????http://files.vector-images.com/image.php?image=baseball3.png

QUIZ 8.18

To make things simple, let's assume that the pitcher throws the ball towards the batter in a direction that is parallel to the ground. (Generally, the pitcher will be throwing down towards batter, partly because the pitcher’s mound is ~10 inches higher than the batter's box.) If the ball is thrown without any spin, what will be the path of the baseball? (Hint: besides the affects of the air which we can ignore for now, what is the only force on the baseball after it has left the hand of the pitcher?)

( ) The baseball will travel in a straight line parallel to the ground.
( ) The baseball will rise on its way to the batter.
( x ) The baseball will drop down on its way to the batter.

Hopefully you selected correctly. Gravity/the weight of the ball will cause the baseball to curve downwards once it leaves the pitcher's hand. By considering the speed of the baseball (~90 miles per hour) and the distance from pitcher's mound to batter's box (60.5 inches) we can calculate the time the ball is in the air (see the next chapter for more on this) and the distance the ball will drop using the equations of motion we discussed in Chapters 1 and 2. Putting this together, I estimate that the baseball will drop ~3 feet due to gravity on the way to the batter. So the path of the baseball without spin will look something like this:

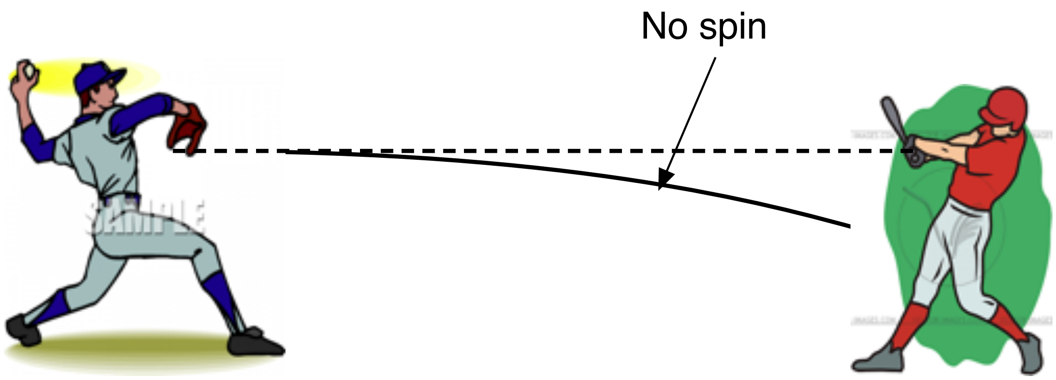



FIGURE 8.22: Schematic of baseball trajectory without spin

So when I say that the baseball is deflected by ~1 foot due to its spin and the Magnus Effect, I mean that the ball is deflected by an additional foot beyond the ~3 foot deflection due to gravity. So the baseball with spin will look like the following:

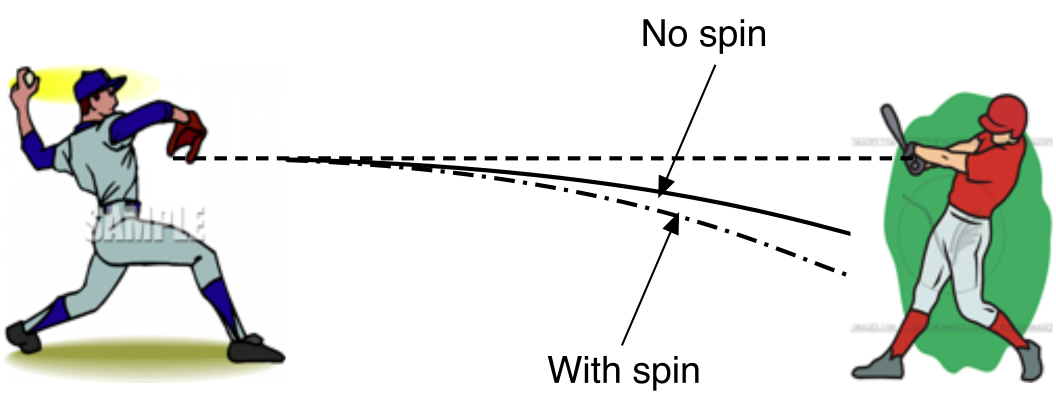



FIGURE 8.23: Schematic of baseball trajectory with spin

The picture above assumes that the ball is spinning with its spin axis parallel to the ground so all the deflection is towards the ground. In general, most breaking balls are thrown with their spin axis in some tilted direction so the baseball will curve down and also either towards or away from the batter. The natural curve ball for a right-handed pitcher is to spin it at an angle such that the ball curves down and away from a right-handed batter; down and towards a left-handed batter; vice-versa for the left-handed pitcher. It's considered a slight advantage to the pitcher when the curve ball curves away from the batter and a slight advantage to the batter when the curve ball curves towards the batter. This is the main reason that there is such attention paid in baseball to the left-left, right-right, and left-right matchups between pitcher and batter and why most bullpens have left-handed and right-handed "specialists" who only pitch to one or a few batters, mainly those with the same handedness. This is also why a switch-hitter sometimes changes the side of the plate from which he bats when there is a pitching change.

Finally, a rough (or dimpled) ball will enhance the Magnus Effect as it does the lift force we discussed earlier. That is another reason why scuffed balls are avoided in professional baseball. A more complete discussion of the Magnus Effect should again include turbulent vs. laminar flow, boundary layer separation, deflected wakes, all topics we will leave alone. In fact, at least one study estimated that Beckham's famous kick benefitted from changes in turbulence during the flight of the ball. If true, did he have some intuition about that when he made the kick? Can you think of other sports in which the Magnus Effect might be important?

## 8.6: Water

Water is a fluid which is important in some sports. Do the same physical laws apply to water as to air? In general, "Yes". We'll examine some of them here. First, let's consider a comparison of swimming and running.

QUIZ 8.19

Let's consider 100 and 200 meter races. In which do you think the athlete is faster (has the shorter time), the swimmer or the runner?

( ) swimmer
( x ) runner
( ) about the same

Did you select correctly? Let's compare gold-medal wining times from the 2008 Olympics:

running:

| | |
|---|---|
| 100 meters: | 9.69 seconds (Usain Bolt, Jamaica) |
| 200 meters | 19.30 seconds (Usain Bolt, Jamaica) |

swimming (freestyle):

| | |
|---|---|
| 100 meters | 47.21 seconds (Alain Bernard, France) |
| 200 meters | 102.96 seconds (Michael Phelps, US) |

You can see that the swimming times are greater than the running times by a factor of ~5. Why is that? Well, there are obviously differences in the muscles used and how they are used in the different sports in propelling the athletes forward. I'm sure that is important. How important, I don't know. That's for someone trained in kinesiology or biomechanics to figure out.

What we can consider here is the physics involved with what the athletes have to push against. The runners are running through the air so they will encounter air resistance as a force acting in the opposite direction from their direction of travel. We know this does have an effect since we claimed earlier in the chapter that a sprinter running in Mexico City, where the air is less dense, could expect a ~2% increase in speed. What about the swimmer?


FIGURE 8.24: Michael Phelps of the U.S. doing the butterfly stroke

https://www.sportphotogallery.com/content/images/cmsfiles/product/17884/17884-list.jpg

Of course, the swimmer travels through water and has to push the water out of the way as he or she proceeds. Or we can think of the water molecules colliding with the swimmer in a similar fashion as air particles for the runner. We already determined that the drag force from air is proportional to: 1. the cross-sectional area, 2. the square of the velocity, and 3. the density of the air. The same relationships hold true for the drag force due to water (with "density of water" substituted for "density of air" in #3).

Lets' now compare each of these parameters and see if we can better understand the differences in running and swimming times:

QUIZ 8.20

Select in each case for which athlete the parameter will be greater:

| | Swimmer | Runner |
|---|---|---|
| 1. Cross-sectional Area | | x |
| 1. Speed | | x |
| 1. Density of fluid (water vs. air) | x | |

Since the runner is more or less upright, the area of his or her body exposed to the air in the travel direction will be considerably more than the swimmer traveling through the water. We already saw that the runner's speed is quite a lot greater than the swimmer's. So both of these factors would result in greater drag force on the runner than the swimmer. However, hopefully you correctly selected that the density of water is greater than the density of air. I think that's pretty obvious. How much greater - by a factor of over 800 (1000 kg/m$^3$ vs. 1.2 kg/m$^3$). Now that will significantly increase the drag force on the swimmer vs. the runner.

Here's another issue regarding a swimmer: The swimmer is pushing against the water more or less in a direction horizontal to the surface to propel himself forward. Why doesn't he sink? Actually some people would sink if they tried to remain motionless in still water. Others would float under the same conditions. We'll consider the floaters. Look at the sketch below of an object "at rest" floating in the water. The object could be a swimmer, a boat, a piece of wood, etc.

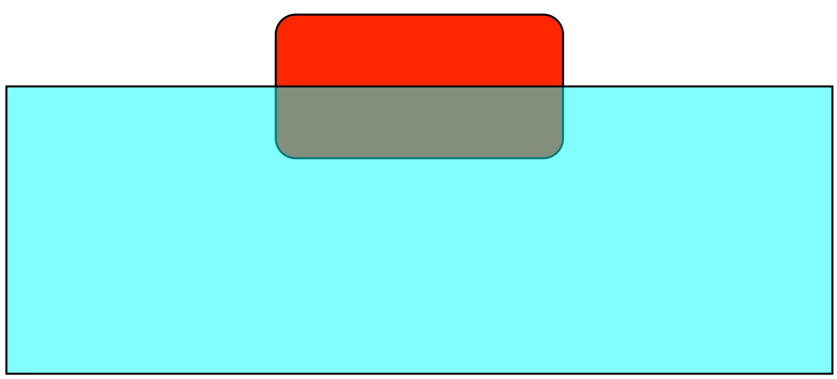


FIGURE 8.25: Sketch of floating object

QUIZ 8.21

Assume the object floating in the water is at rest. Which force or forces that we have studied before are acting on the object? (Choose all that apply.)

( x ) weight
( ) friction
( ) tension
( ) drag force

The weight (acting down) is the only force on the object that we have previously encountered. (No string or rope so no tension; no friction, and no drag force since the object is not moving.) But the object is at rest. There must be at least one more force that acts in the direction opposite the weight, cancelling the force of the weight. Without this balance of forces, the object would have to move (sinking in this case). That opposing force is called the **buoyant force**. A correct sketch showing all the forces on the object looks like this:

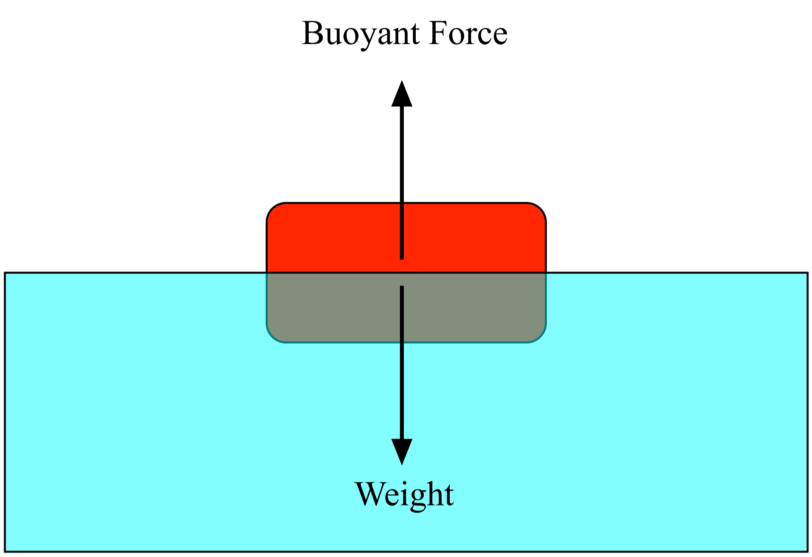



FIGURE 8.26: Free Body Diagram of a floating object

QUIZ 8.22

Assume the object floating in the water has a mass of 20 kilograms. What is the approximate magnitude of the Buoyant Force?

( ) 2 kilograms

( ) 2 Newtons
( ) 20 kilograms
( ) 20 Newtons
( ) 200 kilograms
( x ) 200 Newtons

Since the object is at rest the buoyant force must equal the weight [$mg$ = (20 kg) x (10 m/s$^2$) = 200 N].

Not all objects just float in the water but may sink or rise. Do we know what the buoyant force is equal to in general? Yes, thanks to Archimedes (maybe you have heard of **Archimedes' Principle**) we know that the <u>buoyant force is equal to the weight of the fluid it displaces</u>. We could use this principle to calculate the buoyant force of objects in various fluids and determine, for example, what percentage of an object will be submerged when it is floating.

One value of wearing wet suits for swimmers, besides insulation from cold water, is that they increase the buoyancy of the swimmer, raising him or her up slightly, making it easier to swim through the water.

Air also provides a buoyant force to objects in it but the force is much smaller due to the fact that the density of air is much smaller than the density of water. But it does work as evidenced by the rise of helium-filled and hot air balloons. (Why does the hot air matter?)


FIGURE 8.27: Michael Phelps of the U.S. in a full Bodyskin swimsuit

http://www.scienceinthenews.org.uk/images/contents/8/en/44.jpg

In order to increase swimming speeds, technology has stepped in by designing and constructing special swimsuits that try to mimic the skin of a shark. These suits reduce the drag force in several ways and also increase the buoyancy of the swimmer slightly through trapped air. There was a lot of discussion about them at the 2008 Olympic Games where many swimming records were "smashed." Since then it was decided by FINA, the international body governing water sports, that these swimsuits work too well, and the full body suits have been banned since 2010.

## Chapter 8 Homework

Questions

1. A sky diver jumps out a plane and opens her parachute. What are the forces on the sky diver before she jumps, standing on the floor of the plane? Check all that apply.

(A) weight
(B) friction
(C) tension
(D) air drag
(E) normal force
(F) Magnus Force

Answers: (A), (E)

2. A sky diver jumps out a plane and opens her parachute. What are the forces on the sky diver just as she steps out of the plane? Check all that apply.

(A) weight
(B) friction
(C) tension
(D) air drag
(E) normal force
(F) Magnus Force

Answers: (A)

3. A sky diver jumps out a plane and opens her parachute. What are the forces on the sky diver sometime after she jumps, before she hits the ground.? Check all that apply. (Hint: remember how the sky diver is connected to the parachute.)

(A) weight
(B) friction
(C) tension
(D) air drag
(E) normal force
(F) Magnus Force

Answers: (A), (C), (D)

4. What is the force on a non-spinning basketball that reduces the effects of gravity from ~10 m/s$^2$ to ~9.8 m/s$^2$?

(A) Buoyant force
(B) Drag force
(C) Magnus force

Answer: (A)

5. If you toss a ball straight up into the air, in which direction is the drag force?

(A) up
(B) down
(C) horizontal to the ground

Answer: (B)

6. If a cyclist is traveling due North, in which direction is the drag force?

(A) up
(B) down
(C) North
(D ) South
(E) East
(F) West

Answer: (D)

7. A cyclist doubles his speed. How is the drag force affected?

(A) The drag force is the same.
(B) The drag force is half the original value.
(C) The drag force is one fourth the original value.
(D ) The drag force doubles.
(E) The drag force quadruples.

Answer: (E)

8. With a larger parachute, how will the terminal speed of a parachutist be affected?

(A) The terminal speed will be the same.
(B) The terminal speed will be greater.
(C) The terminal speed will be less.

Answer: (C)

9. Two sky divers jump out of a plane and open their parachutes. One has a parachute that is half the area of the other when fully expanded. Compare the drag forces.

(A) The drag force is the same.
(B) The drag force of the smaller parachute is half the drag force of the larger parachute.
(C) The drag force of the smaller parachute is one fourth the drag force of the larger parachute.
(D) The drag force of the smaller parachute is twice the drag force of the larger parachute.
(E) The drag force of the smaller parachute is four times the drag force of the larger parachute.

Answer: (B)

10. Why was Coors Field in Denver (the "Mile High City") intentionally designed to be the largest baseball playing field?

(A) The temperature is on average colder than at other fields so the balls travel further.
(B) The temperature is on average hotter than at other fields so the balls travel further.

(C) The air density is on average greater than at other fields so the balls travel further.

(D) The air density is on average less than at other fields so the balls travel further.

Answer: (D)

11. You want to set a personal record (PR) in a cycling race. Where are you better off competing: at a meet in Denver (the "Mile High City") or at a meet in Boston (approximately at sea level)?

(A) Denver
(B) Boston

Answer: (A)

12. Why is the terminal velocity of sky diver greater at higher elevation?

(A) The temperature is on average colder at higher elevation.
(B) The temperature is on average hotter at higher elevation.
(C) The air density is on average greater at higher elevation.
(D ) The air density is on average less at higher elevation.

Answer: (D)

13. Compare the range and height of a kicked soccer ball at higher elevation?

(A) The range and height will be the same at higher elevation.
(B) The range will be greater but the height will be the same at higher elevation.
(C) The height will be greater but the range will be the same at higher elevation.
(D ) The range and height will both be greater at higher elevation.
(E ) The range and height will both be less at higher elevation.

Answer: (D)

14. You mistime your swing and hit the top of a golf ball. What happens?

(A) The golf ball heads off in a straight line.
(B) The golf ball curves upwards.
(C) The golf ball curves downwards.

Answer: (C)

15. For a plane in flight, where is the air pressure greater?

(A) Above the wings.
(B) Below the wings.
(C) No difference above or below.

Answer: (B)

16. What force causes a hot air balloon to rise?

(A) weight
(B) friction
(C ) tension
(D ) air drag

(E) normal force
(F) Magnus Force
(G) Buoyant Force

Answer: (G)

16. What force causes a hot air balloon to rise? Explain the physics (and why "hot"?).

17. The terminal velocity of a skydiver under normal conditions is ~110 miles per hour. If the skydiver is plunging through a large cloud, what will happen to the terminal velocity?

(A) The terminal velocity will increase.
(B) The terminal velocity will decrease.
(C) The terminal velocity will stay the same.

Answer: (B)

18. Badwater in Death Valley has the lowest elevation in the U.S., 282 feet below sea level. Where will a cyclist experience a greater drag force?

(A) In Badwater
(B) At sea level
(C) The drag force will be the same at both places.

Answer: (A)

19. Why does a speed skater generally skate in a hunched-over position?

20. Which ball experiences a greater drag force, a well-hit baseball or a softly-hit baseball? Explain.

Answer: Well-hit baseball - greater speed

21. Which ball experiences a greater drag force, a well-hit baseball or a well-hit golf ball? Explain.

Answer: golf ball - greater speed

22. Which ball experiences a greater drag force, a smooth soccer ball or a traditional one with 32 panels? Explain.

Answer: Paneled ball - more roughness

23. Explain why a sports car might have automotive wings and explain why they are "upside down" wings.

24. What is the physics principle behind the flight of a helicopter?

<u>Answer</u>: Bernoulli's Principle

25. Looking down from above, you kick a soccer ball on the left side of the ball.
a. In which direction will it spin?

(A) clockwise
(B) counterclockwise

<u>Answer</u>: (A)

b. In which direction will it curve?

(A) right
(B) left

<u>Answer</u>: (A)

26. Heavy water is water in which the hydrogen atoms are replaced by (more massive) deuterium atoms. The density of heavy water is ~10% greater than the density of "normal" water. How will swimming in heavy water be different?

(A) A swimmer will swim faster in heavy water.
(B) A swimmer will swim slower in heavy water.
(C) There will be no difference.

<u>Answer</u>: (B)

27. Explain why there is a ban on javelin tail-roughening.

28. In what sports is top spin on a projectile desirable in some cases?

<u>Answer</u>: tennis, ping pong, squash, racquetball, basketball,...

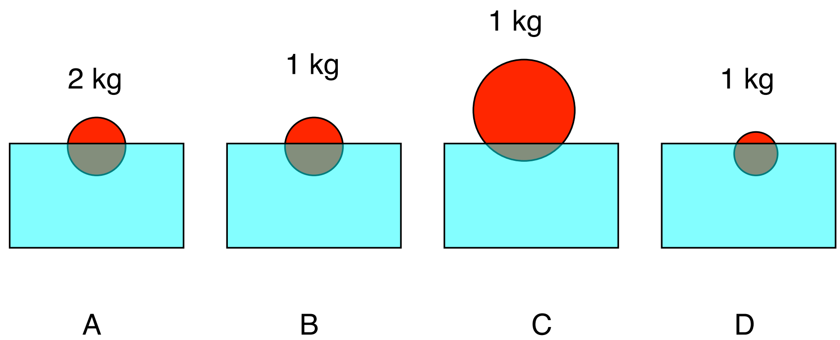
29. In golf, what's a "hook shot"; what's a "slice". What are different between these shots? Explain the physics.

30. A skydiver jumps out of a plane. Compare the terminal speed of the skydiver with and without her parachute deployed.

(A) Her terminal speed is greater with the parachute deployed.
(B) Her terminal speed is less with the parachute deployed.

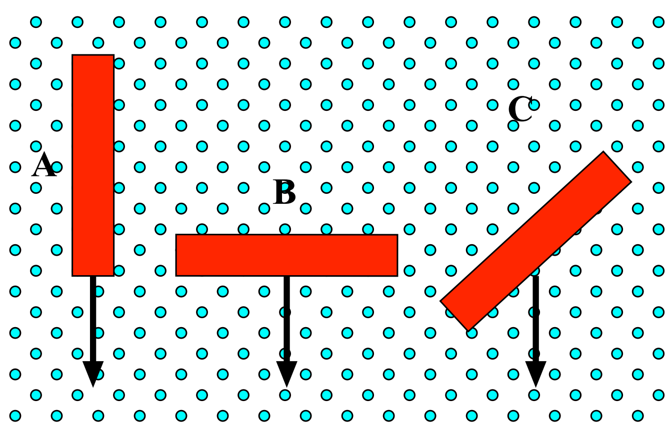
(C) There will be no difference in terminal speeds.

Answer: (B)




31. For the floating balls shown above with masses as given, rank the buoyant forces on the balls.

Answer: A > B = C = D




32. For identical objects falling through the air at the same speed as shown above, rank the magnitude of the drag force on each object.

Answer: B > C > A

33. Why would drafting be illegal in (some) triathlons?

34. In baseball, what's the difference between a curveball, a slider, and a screwball?

35. Assuming the balls are hit at the same speed, which will experience a greater drag force?

(A) a baseball
(B) a softball
(C) There will be no difference in the drag forces.

Answer: (B)

36. a. Does a non-spinning shot experience a lift force after it is thrown?

(A) Yes
(B) No

Answer: (B)

b. Explain.
(symmetric, round, so air flow will be the same on the top and the bottom)

37. An airplane flies into a cloud. How will the lift force be affected?

(A) The lift force will increase.
(B) The lift force will decrease.
(C) There will be no difference in the lift force.

Answer: (A)

## Exercises

1. Under normal conditions, what is the terminal speed of a typical human?

________________ meters per second

Answer: 49 meters per second

2. Under normal conditions the terminal speed of a typical human is ~50 meters per second.

a. If there were no drag force, approximately how long would it take a sky diver in free fall to reach this speed?

________________ seconds

Answer: 5 seconds

b. Explain why it takes ~10 seconds for a skydiver to reach terminal speed under a normal amount of drag force.

3. Two similar sky divers jump out of a plane and open their parachutes. The drag force on one diver is 500 Newtons. The other diver has a parachute that is 50% larger. What is the drag force on this diver?

________________ Newtons

Answer: 750 Newtons

4. The drag force on a cyclist is 5 Newtons. He doubles his speed. What will be the drag force now?

________________ Newtons

Answer: 20 Newtons

5. If a smooth golf ball traveled 100 yards, how far will a dimpled golf ball travel?

________________ yards

Answer: 175 yards

6. The Magnus force on a golf ball spinning at 1000 revolutions per minute is 0.1 Newton. If the same golf ball were spinning at 2000 revolutions per minute, what would be the Magnus force?

________________ Newtons

Answer: 0.2 Newtons

7. By what factor will the drag force on a swimmer change if she increases her speed by 50%?

(A) 1.5
(B) 2
(C) 2.25
(D) 2.5
(E) 5

Answer: (C)

8. Heavy water is water in which the hydrogen atoms are replaced by (more massive) deuterium atoms. The density of heavy water is ~10% greater than the density of "normal" water. If the drag force on a swimmer in normal water is 100 Newtons, what is the drag force on the swimmer in heavy water?

________________ Newtons

Answer: 110 Newtons

9. A swimmer is swimming with a speed of 2 meters per second and is experiencing a drag force of 100 Newtons. If she slows down to 1 meter per second, what will be the new drag force?

________________ Newtons

Answer:  25 Newtons

10. A swimmer is swimming with a speed of 2 meters per second and is experiencing a drag force of 100 Newtons. If she speeds up to 2.5 meters per second, what will be the new drag force?

________________ Newtons

Answer:  156 Newtons

11. A person with a weight of 600 Newtons is floating in a pool. What is the magnitude of the Buoyant Force on the swimmer?

________________ Newtons

Answer:  600 Newtons

12. A person with a mass of 50 kilograms is floating in a pool. What is the magnitude of the Buoyant Force on the person?

________________ Newtons

Answer:  500 Newtons

13. A person with a mass of 50 kilograms is floating in a pool of heavy water. Heavy water is water in which the hydrogen atoms are replaced by (more massive) deuterium atoms. The density of heavy water is ~10% greater than the density of "normal" water.
a. What is the magnitude of the Buoyant Force on the person?

________________ Newtons

Answer:  500 Newtons

b. Is more or less heavy water displaced compared with the swimmer floating in "normal" water?

(A) more heavy water is displaced
(B) less heavy water is displaced
(C) the same volume of heavy water as normal water is displaced

Answer: (B)

14. A skydiver jumps out of an airplane, falls and eventually reaches his terminal speed.
a. Assuming the weight of the skydiver is 800 Newtons, what is the drag force on the skydiver at this time?

________________ Newtons

b. One second later, what has happened to the drag force on the skydiver?

(A) the drag force has increased
(B) the drag force has decreased
(C) the drag force is the same

Answers: a. 800 Newtons
b. C

15. The Boeing 747-8 airplane has four wings (2 smaller ones at the tail) and a maximum mass of ~440,000 kilograms. Assuming that the force is equally distributed among the four wings (why is this not a good assumption?), what is the minimum lift force per wing needed for the plane to take off?

________________ Newtons

Answer: 1,100,000 Newtons

16. A 60 kilogram swimmer is floating in a pool on Earth.

a. What is the buoyant force on the swimmer?

________________ Newtons

b. At another time, the same swimmer is floating in a pool on the Moon, where the force of gravity is ~1/6 that on Earth. What is the buoyant force on the swimmer?

________________ Newtons

Answers: a. 600 Newtons
b. 100 Newtons

17. A golf ball may spin as much as 4000 revolutions per minute. What is the angular speed of the golf ball?

________________ radians per second

Answer: 419 radians per second

18. On Planet XXX, the acceleration due to gravity is 5 $m/s^2$. An astronaut on the planet jumps off a cliff. His speed increases as follows: 5 m/s after 1 second, 10 m/s after 2 seconds, 15 m/s after 3 seconds, 20 m/s after 4 seconds. What can you conclude about the density of air on Planet XXX compared with the density on Earth?

________________

Answer: There is no air on Planet XXX.

19. The terminal speed of a human is ~50 meters per second under normal conditions. If a skydiver is falling through air that has 1/2 the density of the air that is just above the Earth's surface, what will be the terminal speed of the skydiver?

________________ meters per second

Answer: 71 meters per second

20. A soccer ball has a mass of ~0.425 kilogram and a volume of ~5.8 $cm^3$.
a. What is the buoyant force due to the air on a soccer ball?

_______________ Newton

b. If the soccer ball were floating in water, what would be the buoyant force?

_______________ Newtons

Answers: a. $6.95 \times 10^{-5}$ Newton
b. 4.25 Newtons

21. The Antonov An-225, built in 1988, is the world's heaviest aircraft with a maximum takeoff mass (with cargo) of 640,000 kilograms. Its volume is approximately 40,000 $m^3$.

a. What is the buoyant force on the plane?

_______________ Newtons

b. At its maximum weight, what is the lift force on the plane?

_______________ Newtons

c. What is the ratio of buoyant force to lift force?

_______________

Answers: a. 480,000 Newtons

b. 5,920,000 Newtons
c. 0.081

22. The AC72 catamaran was being developed for the America's Cup race in 2013. The boat has a mass of 5800 kilograms.

a. What is the buoyant force on the boat while it is floating in the water?

________________ Newtons

b. How much water does the boat displace while it is floating?

________________ $m^3$

Answers: a. 58,000 Newtons
b. 5.8 $m^3$

23. A boat floating in the water displaces a water volume of 1.0 $m^3$. Find the mass of the boat.

________________ kilograms

Answer: 1000 kilograms

# CHAPTER 9: Time


False start in the 100 meter dash at the 2011 Track and Field World Championships

http://i.dailymail.co.uk/i/pix/2011/08/28/article-2031053-0D9B244100000578-800_468x313.jpg


VIDEO 9.1:
False start in the 100 meter dash at the 2011 Track and Field World Championships

https://digitalcommons.uri.edu/physicsofsports/43/

Select and watch VIDEO 9.1.

## 9.1: Starting Time

Time is a very important element in most if not all sports. Many sports work off a clock such as 20 minute periods in hockey, 15 minute quarters in football, the 24 second shot clock in professional basketball (30 or 35 seconds in college basketball), and the mysterious "extra time" at the end of soccer games. In addition to these times, split second timing is critical to many athletic performances and is the main subject of this chapter.

One example is shown in the video you just watched. Usain Bolt, whose performances we have analyzed and discussed previously, was disqualified from the 100 meter race in the 2011 World Championships held in South Korea for "jumping the gun" at the start of the race. International rules are so strict that you only get one chance and then you are out.

Actually, officials at high profile shorter races don't use a gun or starting pistol anymore. Instead, an electronic buzzer goes off at the feet of each runner. (See Figure 9.1 below).


FIGURE 9.1: Runners at the Start of a 100m race

https://c8.alamy.com/comp/CY1PHF/start-of-womens-heptathlon-100m-race-at-the-olympic-summer-games-london-CY1PHF.jpg

Why not the gun? Let's imagine 8 runners lined up side-by-side and poised to take off. The official standing off to the side of the runner in lane #1 shoots off a starting pistol. Is this fair?

QUIZ 9.1

What about the runners when the official shoots off his gun?

| | |
|---|---|
| ( ) | It's fair - all runners hear the gun going off at exactly the same time. |
| ( x ) | It's not fair - the runner nearest the official hears the gun go off first. |
| ( ) | It's not fair - the runner nearest the official hears the gun go off last. |

I hope you chose correctly that the runner closest to the gun would hear the sound first. But by how much time? That's the issue! Even though the time delay between runners hearing a starting pistol is very short, a fraction of a second can make a difference in who wins or loses or places in a race. So no starting pistols anymore, at least in many such (short distance) events.

QUIZ 9.2

Let's estimate the time delay of hearing a starting pistol between runners starting on opposite sides of the track. A lane width is 4 feet by international standards, so the distance from the runner in the middle of lane 1 to lane 8 is 7 x 4 = 28 feet; let's round to 30 feet. The speed of sound of the gun, which is what the runners used to start from, is ~1100 feet per second; we'll round off to 1200 feet per second. So what is the approximate time delay from lane 1 to lane 8:

| | |
|---|---|
| ( x ) | 0.025 second |
| ( ) | 0.050 second |
| ( ) | 0.25 second |
| ( ) | 0.50 second |
| ( ) | 1 second |
| ( ) | 4 seconds |

We got this time by dividing the distance by the speed of sound.

That seems like a short time, but "short" is relative (and not a physics term anyway!). What should we compare that time to? First, remember Bolt's 100 meter world record in the

2008 Olympics, we watched in the first chapter? His gold medal time was 9.69 seconds. So 0.025 seconds is certainly much smaller than that. The time of the silver medalist (Richard Thompson, Trinidad and Tobago) was 9.89 seconds, a 0.2 second difference, still a factor of 10 greater than the time delay we calculated. However, the time of the bronze medalist (Walter Dix, US) was 9.91 seconds, only 0.02 second behind the second place finisher. I think you can see why the gun had to go.

Obviously, as the races get longer (in time and in distance) this time delay is not as important. That explains why for longer races starting blocks are no longer used and some sort of starting pistol is still o.k. Which races would those be? I think that it would also be interesting to look at the separation times for the first few finishers in longer races.

In what other sports do you think the starting time is also critical?

## 9.2: Reaction Time

A key element in the split-second timing in many sports such as the race we just examined is the reaction time of the athlete. You can probably guess that some people possess shorter reaction times than others. Also, you might imagine that one's reaction time can be shortened through practice, but probably within limits. At some level the body's physiology comes into play and sets some more or less absolute limits on reaction times. (That's about all I know about this topic.)

Before we look at the reaction times of athletes, you're going to determine your own reaction time using three different tests. In each case, you will carry out 5 trials and record the average, then take the average of those 3 tests. The first two you will find on the web. (If either of these reaction time tests are no longer available on the web, I'm sure you can find some others.) The third test will require a partner and some "hands on" work.

QUIZ 9.3

Reaction Time Test 1:

http://getyourwebsitehere.com/jswb/rttest01.html

Test 1 Average Reaction Time (5 trials): _______________ second

QUIZ 9.4

Reaction Time Test 2:

http://www.exploratorium.edu/baseball/reactiontime.html

Test 2 Average Reaction Time (5 trials): _______________ second

Reaction Time Test 3:

http://worldofcaffeine.com/wp-content/uploads/2011/03/reaction-time-ruler-test.jpg

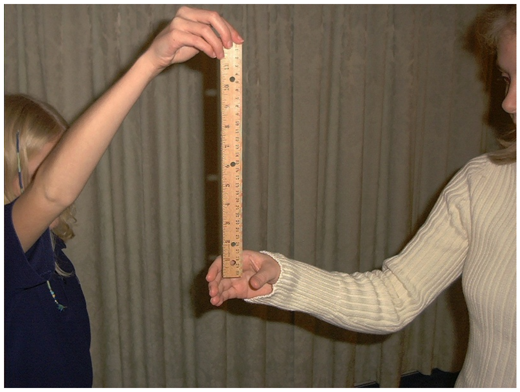


FIGURE 9.2: Arrangement for Reaction Time test #3

The way this test works is as follows:

1. Your partner holds a ruler with centimeter markings such that the bottom of the ruler is poised between your fingers and thumb, as shown in the image above.
2. At a "random" time, your partner releases the ruler. You grab it as soon as you can.
3. You measure the distance the ruler fell.

QUIZ 9.5

If the ruler falls a longer distance, is your corresponding reaction time shorter or longer?

( ) shorter
( x ) longer

4. You convert that distance into a reaction time by inputting the distance into the calculator at the following web site:

   http://www.brianmac.co.uk/rulerdrop.htm

5. Repeat 4 more times and record the average below.

QUIZ 9.6

Test 3 Average Reaction Time (5 trials): _______________ second

QUIZ 9.7

Net Average Reaction Time: _______________ second

(Answer: Average of previous 3 quizzes)

I came up with a reaction time for myself of 0.378 second. Not too impressive (I hate to say it but research shows that reaction time increases with age!), though I did have the feeling that I could improve with a little practice. How did you do? Was the result of each test similar? If so, that should give you more confidence in the results.

So what is the average human reaction time? There are different kinds of reaction time (a subject outside of this course) and many different ways to measure them and many factors such as age to consider. That said, looking at a range of studies most values fall in the 0.15-0.3 second range (making my time seem even worse!) with most times from 0.2-0.25 second.

What about athletes? Do you think their reaction times are better than average? I would assume that in many cases the answer is "Yes", especially in those sports or sport activities for which reaction time is particularly important. But again, there are limits set by our physiology (also a subject for another course).

I have noticed that in some track events, the reaction times are listed as part of the results. For example, when Bolt broke his own world record (set at the 2008 Summer Olympics) in the 100 meter dash at the 2009 Track and Field World Championships held in Berlin, his reaction time was listed as 0.146 second. I assume this is the time delay from the electronic beep that started the race to the time his foot was detected to have left the starting block.

## 9.3: Reaction Time 2

Now let's look at some examples in sports in which reaction time is important. I'm sure you can come up with many more examples. We'll only discuss a few.

First, I want to return to the race we watched earlier, when Usain Bolt was disqualified for anticipating the start. Knowing that human reaction times are in most or all cases greater that 0.15 second, the IAAF (International Association of Athletic Federations) instituted a new rule in 2002 regarding false starts in sprint races using starting blocks (which have sensors in them). Now any athlete who leaves the starting block in less than 0.1 second after the starting buzzer sounds will be disqualified as it is assumed that he or she "jumped the start". That's science and technology in action! Note that in the 2009 race discussed above, Bolt left the starting block 0.146 second after the start of the race - within legal limits this time.

Now let's turn to a few key examples of timing and reaction times in baseball. The question: How much time does the batter have to hit the pitched ball? (Roughly this is the setup of reaction time test #2.) By this I mean how much time elapses from the moment the ball leaves the pitcher's hand to the moment the bat and ball make contact? We'll need some numbers. Let's take a look at a baseball diamond with dimensions included:

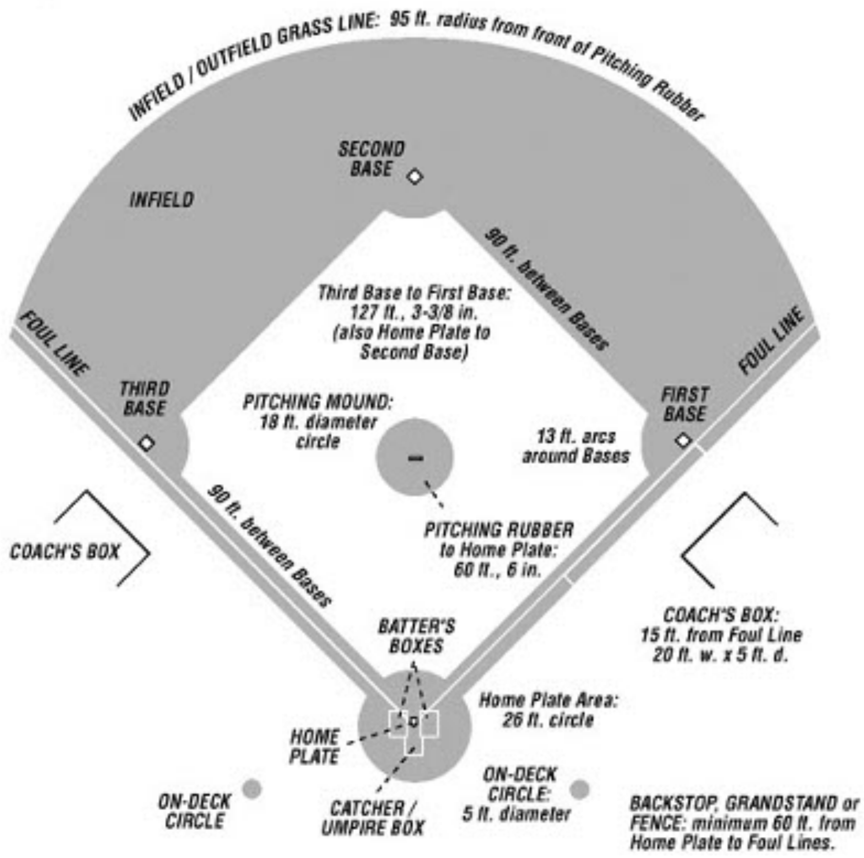



FIGURE 9.3: Schematic of a professional baseball field

http://3.bp.blogspot.com/_4DZeuZWSETU/TRDNepyvw6I/AAAAAAAABgM/EPEM4Cv1Ptc/s400/baseball_diamond.jpg

Assume the pitcher launches a fastball at home plate with a speed (assumed constant) of 90 miles per hour (that's ~132 feet per second).

QUIZ 9.8

How long does it take the ball to cross home plate?

_____________ second

(Answer: 0.46 second)

That came from dividing the distance from the pitcher's mound to home plate (60.5 feet) by the speed of the fastball.

Now we'll take a look at a video clip and see if we can get a similar time for the ball's journey from pitcher's hand to home plate and also estimate the time it takes a batter to swing his bat. Select VIDEO 9.2 and watch Dustin Pedroia of the Boston Red Sox hit a home run in the first at bat of the 2007 World Series. (The Red Sox went on to defeat the Colorado Rockies in a 4-game sweep.)


VIDEO 9.2: First at bat of the 2007 World Series

https://digitalcommons.uri.edu/physicsofsports/44/

Now go back to the video and advance frame-by-frame through the sequence during which the pitched ball leaves the pitcher's hand and makes contact with the bat. Count the number of frames.

QUIZ 9.9

How many frames were needed to get the ball from pitcher's hand to bat?

_____________ frames

(Answer: ~13 frames)

I came up with 13 frames. How about you? Now we can convert the frame number into a time by using the fact that the video was captured at a rate of 30 frames per second. Using my number of 13 frames, calculate the time.

## QUIZ 9.10

How much time did it take for the baseball to travel from the pitcher's hand to the bat? (Use 13 frames and 30 frames per second.)

( ) 0.22 second
( x ) 0.43 second
( ) 0.86 second
( ) 2.3 seconds
( ) 4.6 seconds

A time of 0.43 second was very close to our estimate above of 0.46 second for a 90 mph fastball. Very good!

Now let's look at the batter. How long does it take Dustin Pedroia to swing his bat? We can do the frame-by-frame analysis again but first we need to decide when to start counting (the end is obvious - when the bat makes contact with the ball). The batting sequence went something like this: From a fairly relaxed position he lifts his front foot, shifts his weight to the rear, then leans forward onto his front foot as he swings the bat around. It's somewhat subjective, but let's start counting frames from the first frame in which he starts to lower his front foot. See what you come up with.

## QUIZ 9.11

How many frames did it take the batter to complete his swing?

____________ frames

(Answer: ~9 frames)

I came up with 9 for this activity though 8 or 10 would also be reasonable. What about you?

What does this mean. 9 frames = ~0.3 second, less than the time it takes the ball to reach home plate. But we are forgetting something important; the subject of the last two sections of the chapter - reaction time. Let's assume a reaction time for Pedroia of 0.2 second. Now how long before he hits the ball did he <u>decide</u> to swing the bat? Well, we have to add 0.2 + 0.3 = 0.5 second. This is the point. The batter must decide to swing the bat <u>before</u> the baseball leaves the pitcher's hand! No wonder batters often swing at pitches way outside the strike zone and no wonder it is so difficult to be a successful hitter in professional baseball! I'd say it is quite remarkable that a top hitter not only makes contact with the baseball but gets a hit one out of every three times he comes to bat.

Example #2, also from baseball: stealing second base. In Chapter 1, we watched the video below (VIDEO 9.3) of Ichiro Suzuki of the Seattle Mariners stealing second base and made an estimate of the time of the steal. Now let's do a better job of getting the time by counting frames from when he starts his dash to when he tags second base. Watch the video and then record your answer below.

VIDEO 9.3: Ichiro Suzuki steals 2nd base
(Seattle Mariners vs. New York Yankees)

https://digitalcommons.uri.edu/physicsofsports/45/

QUIZ 9.12

How many frames did it take for Suzuki to steal second base? (I know that Ichiro disappears from view for a few frames but do your best.)

____________ frames

(Answer: ~80 frames)

I came up with 80 frames though anywhere from 75-85 would also be reasonable. What about you? If we use 80 frames, how long did it take him to steal the base? The capture rate on this video was 25 frames per second, which gives a time of 80/25 = 3.2 seconds. In Chapter 1, I had made a cruder estimate by measuring the time directly as 3 seconds, so not too bad.

What about that time? Long? Short? What do we compare it to, which is related to the issue of how hard it is to steal a base. It must be fairly difficult or everyone would do it. I say we need to know how long it takes the ball to travel from pitcher to catcher and then for the catcher to make a throw to second base.

We already calculated that it takes ~0.46 second for the ball to get from the pitcher to home plate. How long does it take the catcher to throw the ball to second base? Maybe a close look at a video would give us a better number but let's just estimate from the distance between home plate and second base (see the previous diagram of the baseball field) and the speed with which the catcher throws the ball. A major league catcher has to have a strong throwing arm just for this reason but he's not throwing at 90-100 mph either. If he could do that, he would be a pitcher! I'm going to just guess at a throwing speed in the 75 mph range. Let's use that.

QUIZ 9.13

How long does it take for the catcher to get the ball from home plate to second base assuming an average speed of 75 mph (which converts to ~110 feet per second)?

____________ seconds

(Answer: 1.16 seconds)

Now we add these times together: 0.46 + 1.16 = 1.62 seconds. Do we also need to consider reaction times? Well, the base stealer needs ~0.2 second to start his move after he decides to go for it. The catcher needs some time from his decision to throw to second base to actually starting his throw, though I imagine a good catcher is already processing this as he is waiting for the ball to be delivered from the pitcher to his mitt. Also, the catcher requires some time to gather up and make the throw (how long - I don't know - check it out).

Well, whether you include these additional times or not, we have found that the runner needs ~3 seconds to steal the base, but it takes only about half this time or less to get the ball into the hands of the second baseman (an accurate throw is needed also of course). Clearly good anticipation or guessing or luck is needed for the base stealer to be successful on a regular basis.

Example #3 is from hockey. The question I want to look at this time is how long does the goal keeper have to block a slap shot fired at the goal? Select VIDEO 9.4 and watch Nathan Horton shoot the overtime game-winning and series-winning goal in game 7 of the 2011 NHL Eastern Quarterfinals between the Boston Bruins (who went on to win the Stanley Cup) and the Montreal Canadians. Again, a bit of a challenge, but I want you to try to count the number of frames it took the hockey puck to travel from Horton's stick across the goal line (you'll have to guess a little on this part - do your best).


VIDEO 9.4: Overtime Goal in Game 7 of the 2011 NHL Eastern Quarterfinals

https://digitalcommons.uri.edu/physicsofsports/46/

QUIZ 9.14

How many frames did it take for the hockey puck to get from stick to goal?

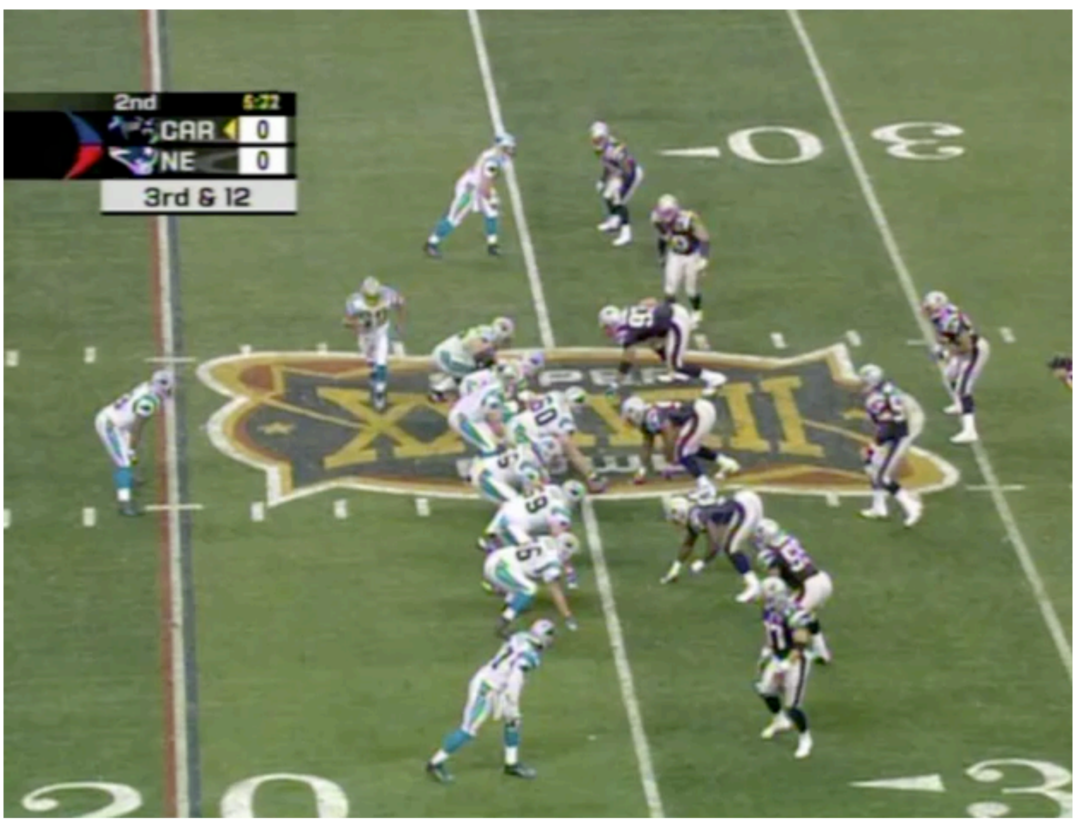
____________ frames

(Answer: 14 frames)

I came up with 14 frames but there is some margin of error on that as you saw. Was that close to your estimate?

So the length of time involved using that number and a capture rate of 25 frames per second is 14/25 = 0.56 second. Now given that the reaction time of the goalie is ~0.2 second, he only has ~0.35 second to block the shot - a real challenge that obviously did not work out in this case. You can see why even a slightly shorter reaction time is a great benefit in this sport at the goalie position.

The last example in this section is from football. I want to know how long the quarterback can hold onto the football. If he holds it too long the usual result is that he gets sacked, not a good thing. Select VIDEO 9.5 and watch linebacker Mike Vrabel of the New England Patriots sack quarterback Jake Delhomme of the Carolina Panthers in Super Bowl XXXVIII (New England went on to win this game with a score of 32-29 with a last second field goal). I want you once again to count the frames from the time the football is snapped to the time of the sack of the quarterback. As usual, you'll have to estimate and use your judgment. Let's call the time of the sack as the time at which the defensive player first touches the quarterback.



VIDEO 9.5: Quarterback Sack in Super Bowl XXXVIII

https://digitalcommons.uri.edu/physicsofsports/47/

QUIZ 9.15

How many frames did you count from the snap of the football to the sack of the quarterback?

____________ frames

(Answer: ~80 frames)

I came up with 80 frames. How about you? At 25 frames per second, that turns into a time of ~3.2 seconds. To get a better idea of an average "sack time", I analyzed all the sacks in this Super Bowl and in Super Bowl XXXIX (8 sacks in total, 4 in each game) and got an average sack time of 3.05 seconds. This is a relatively long time compared to some other times we have looked at. But there is a lot going on: The quarterback needs time for the play to develop, for the receiver to get off the line of scrimmage and run his route and get in the clear.

Reaction times involved include the reaction times of the offensive linebackers defending the quarterback and of the defense trying to put pressure on and sack the quarterback. (If the defenseman tries to anticipate the snap count and jumps too early, he gets hit with a 5 yard offsides penalty - better at least than being disqualified like Bolt was!) Also the quarterback must try to elude these defenders and also make a quick decision to throw the football. Considering all this, 3 seconds is not that long!

O.k. that's it for this chapter. I'm sure you can think of many other examples where timing and reaction times are important in sports. Just about any time a ball or other projectile is thrown or hit at another player (tennis, badminton, volleyball, jai alai, hurling, ...) or a fast race is taking place (hurdles, speed skating, skiing, cycling, ...). In fact, it's probably harder to think of sports in which time or timing is <u>not</u> important. Can you come up with any?

## Chapter 9 Homework

Questions

1. For which running race is "jumping the gun" a more important issue?

(A) 100 meter dash
(B) 5K (5 kilometer) race

Answer: (A)

2. For which event is "jumping the gun" a more important issue?

(A) 100 meter dash (running)
(B) 100 meter butterfly (swimming)

Answer: (A)

3. Name other sporting events in which the starting time is critical.

(speed skating, rowing, cycling, ...)

4. It seems reasonable to assume that there are reaction times associated with most or all of the senses and that these reaction times are generally going to be different. Let's consider touch, hearing, and sight. For which do you think the reaction time will be the least? greatest?

Partial Answer: auditory < touch < visual

(I'm not sure about other senses.)

5. Name some sports in which reaction times are not important.

(bowling, curling, marathon race, long bicycle races)

6. You watch the start of a race from the stands. The track official shoots off a starting pistol.
a. Which do you detect first?

(A) smoke from the pistol
(B) sound of the pistol

Answer: (A)

b. Explain.

Answer: Speed of light is greater than the speed of sound.

7. While you are watching from the stands, a baseball player hits a homerun.

a. Which do you detect first?

(A) sound of bat hitting ball
(B) seeing the ball leave the bat

Answer: (B)

b. Explain.

Answer: Speed of light is greater than the speed of sound.

8. You may have heard that to estimate how far away a storm is you should count the seconds between seeing a lightning strike and hearing a thunderclap. Explain the physics behind this.

Answer: Speed of light is greater than the speed of sound.

9. In a running race when all 8 lanes are occupied and in which a starting pistol was used, the time difference between the top two finishers was 0.01 second. Explain some possible problems with this race.

Answers: Time difference less than time delay between lanes 1 and 8; time difference less than a reaction time.

10. Discuss Bolt's 100 meter dash world record times (9.69 seconds in 2008; 9.58 seconds in 2009) in the context of his reaction time.

11. If a flash of light was used instead of a starting pistol to start a race, would it make any difference? Explain.

12. In base stealing in baseball, the runner tried to start his sprint to the next base as soon as possible. If he leaves too early, what happens?

13. In baseball, to try to prevent a base from being stolen, sometimes the pitcher and catcher will perform a "pitchout" in which the pitcher throws the ball to the catcher who is in a standing position to receive it? What is the possible advantage of a pitchout?

14. You take a reaction time test. The results tell you that your reaction time is 0.98 second. Is this reasonable? Explain.

15. The goal of some punters in football is to keep the football in the air as long as possible.
a. What is the advantage in doing this?

b. When would a punter not want to keep the ball in the air as long as possible?

## Exercises

1. At a track meet, calculate the time delay from the moment the starting gun goes off (if a gun were still used) until a viewer in the stands 50 feet from the starting official hears the gun. (Use the speed of sound as 1100 feet per second.)

________________ seconds

Answer: 0.045 second

2. At a baseball game, a baseball player hits a home run while you are watching from the stands 450 feet away. Calculate the time delay from the moment the bat collides with the ball to the time you hear the crack of the bat. (Use the speed of sound as 1100 feet per second.)

________________ seconds

Answer: 0.41 second

3. At a track meet, assume a runner "jumps the gun" by 0.1 second. If his average speed is 5 meters per second, how far will he have run before the gun goes off?

________________ meters

Answer: 0.5 meter

4. At a swim meet, assume a swimmer "jumps the gun" by 0.1 second. If his average speed is 1 meter per second, how far will he have swum before the gun goes off?

________________ meter

Answer: 0.1 meter

5. For the 60 meter dash, assume a runner's average speed is 10 meters per second. How many "reaction times" of 0.2 second does it take for the sprinter to complete this race?

________________ reaction times

Answer: 30 reaction times

6. For a 10K race (10 kilometers), assume a runner's average speed is 6 meters per second (near the current world record). How many "reaction times" of 0.2 second does it take for the runner to complete this race?

_______________ reaction times

Answer: 83,333 reaction times

7. Nerve signals travel through the body at a speed of ~25 meters per second (56 miles per hour).

a. Find the time it takes a nerve impulse to travel from you hand to your brain. Assume a distance of 1 meter.

_______________ second

b. The human body contains ~46 miles of nerves. Find the time it takes a nerve impulse to travel this entire distance.

_______________ minutes

Answers: a. 0.04 second
b. 49.4 minutes

8. Compute the ratios of a reaction time of 0.2 second to the men's world record times for these 50 meter races:

a. 50 meter running (Donovan Bailey of Canada in 1996)
Race time = 5.56 seconds

Ratio = ____________

b. 50 meter swimming freestyle (Cesar Cielo of Brazil in 2009)
Race time = 20.91 seconds

Ratio = ____________

Answers:

a. 0.036
b. 0.0096

9. Compute the ratios of a reaction time of 0.2 second to the men's world record times for these running races:

a. 50 meter (Donovan Bailey of Canada in 1996)
Race time = 5.56 seconds

Ratio = ____________

b. 100 meter (Usain Bolt of Jamaica in 2009)
Race time = 9.58 seconds

Ratio = ____________

c. 200 meter (Usain Bolt of Jamaica in 2009)
Race time = 19.19 seconds

Ratio = ____________

d. 400 meter (Michael Johnson of U.S. in 1999)
Race time = 43.18 seconds

Ratio = ____________

e. 5 kilometer (Kenenisa Bekele of Ethiopia in 2004)
Race time = 12 minutes and 27.35 seconds

Ratio = ____________

f. Marathon (42.195 kilometers) (Samuel Kamau Wanjiru of Kenya in 2008)
Race time = 2 hours, 6 minutes, and 32 seconds

Ratio = ____________

Answers:

a. 0.036
b. 0.0021
c. 0.010
d. 0.0046
e. 0.00027
f. 0.000026

10. Compute the ratios of the men's world record times for these swimming vs. running races:

a. 50 meter running (Donovan Bailey of Canada in 1996)
Race time = 5.56 seconds

50 meter swimming freestyle (Cesar Cielo of Brazil in 2009)
Race time = 20.91 seconds

Ratio = ____________

b. 100 meter running (Usain Bolt of Jamaica in 2009)
Race time = 9.58 seconds

100 meter swimming freestyle (Cesar Cielo of Brazil in 2009)
Race time = 46.91 seconds

Ratio = ____________

c. 200 meter running (Usain Bolt of Jamaica in 2009)
Race time = 19.19 seconds

200 meter swimming freestyle (Paul Biedermann of Germany in 2009)
Race time = 1 minute and 46 seconds

Ratio = ____________

d. 400 meter running (Michael Johnson of U.S. in 1999)
Race time = 43.18 seconds

400 meter swimming freestyle (Paul Biedermann of Germany in 2009)
Race time = 3 minutes and 40.07 seconds

Ratio = ____________

e. 1500 meter running (Hicham El Guerrouj of Morocco in 1998)
Race time = 3 minutes and 26 seconds

1500 meter swimming freestyle (Sun Yang of China in 2011)
Race time = 14 minutes and 34.14 seconds

Ratio = ____________

Answers:

a. 3.76
b. 4.90
c. 5.52
d. 5.10
e. 4.24

11. Compute the average speeds of the men's world record times for these running races:

a. 50 meter (Donovan Bailey of Canada in 1996)
Race time = 5.56 seconds

____________ meters per second

b. 100 meter running (Usain Bolt of Jamaica in 2009)
Race time = 9.58 seconds

____________ meters per second

c. 200 meter running (Usain Bolt of Jamaica in 2009)
Race time = 19.19 seconds

____________ meters per second

d. 400 meter running (Michael Johnson of U.S. in 1999)
Race time = 43.18 seconds

____________ meters per second

e. 800 meter running (David Rudisha of Kenya. in 2010)
Race time = 1 minute and 41.01 seconds

____________ meters per second

f. 1500 meter running (Hicham El Guerrouj of Morocco in 1998)
Race time = 3 minutes and 26 seconds

____________ meters per second

g. 5 kilometer (Kenenisa Bekele of Ethiopia in 2004)
Race time = 12 minutes and 27.35 seconds

____________ meters per second

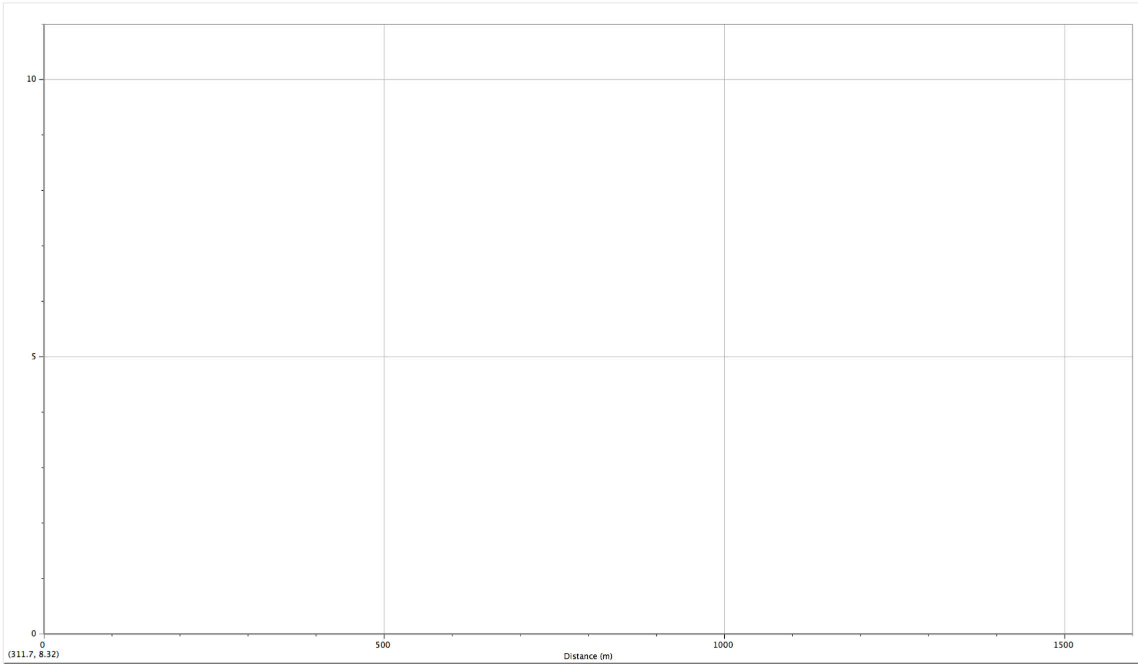
h. Marathon (42.195 kilometers) (Samuel Kamau Wanjiru of Kenya in 2008)
Race time = 2 hours, 6 minutes, and 32 seconds

____________ meters per second

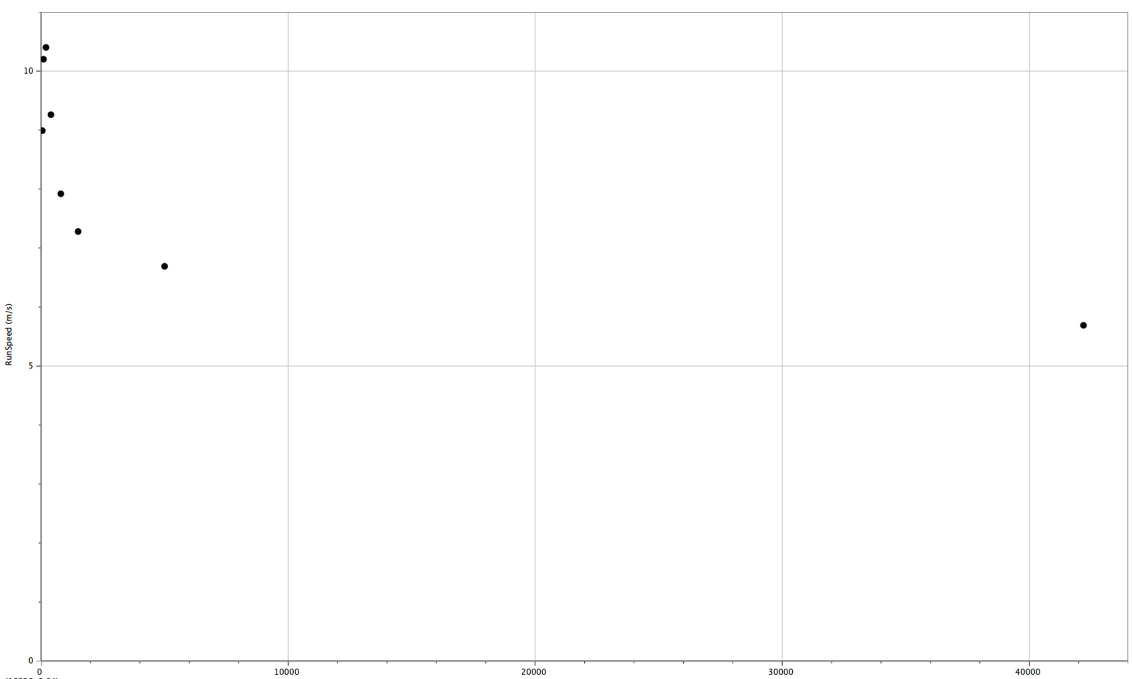
<u>Answers:</u>

a. 8.99 meters per second
b. 10.2 meters per second
c. 10.4 meters per second
d. 9.26 meters per second
e. 7.92 meters per second
f. 7.28 meters per second
g. 6.69 meters per second
h. 5.69 meters per second

12. Plot the average speeds vs. race distance for the running race data of problem #9.


10
5
0
0
500
1000
1500
(311.7, 8.32)
Distance (m)

Answer:


RunSpeed (m/s)
10
5
0
0
10000
20000
30000
40000
(18026, 6.04)
Distance (m)

13.  Compute the average speeds of the men's world record times for these swimming races:

a.  50 meter swimming freestyle (Cesar Cielo of Brazil in 2009)
Race time = 20.91 seconds

____________ meters per second

b.  100 meter swimming freestyle (Cesar Cielo of Brazil in 2009)
Race time = 46.91 seconds

____________ meters per second

c.  200 meter swimming freestyle (Paul Biedermann of Germany in 2009)
Race time = 1 minute and 46 seconds

____________ meters per second

d.  400 meter swimming freestyle (Paul Biedermann of Germany in 2009)
Race time = 3 minutes and 40.07 seconds

____________ meters per second

e.  800 meter swimming freestyle (Zhang Lin of China in 2009)
Race time = 7 minutes and 32.12 seconds

____________ meters per second

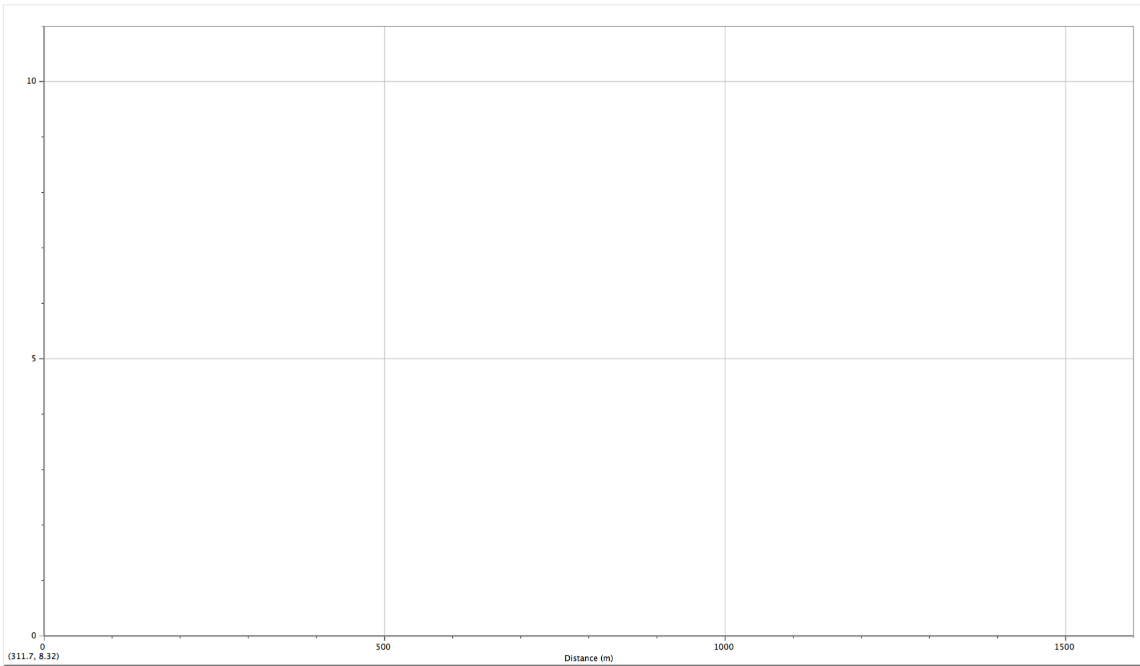
e.  1500 meter swimming freestyle (Sun Yang of China in 2011)
Race time = 14 minutes and 34.14 seconds

____________ meters per second

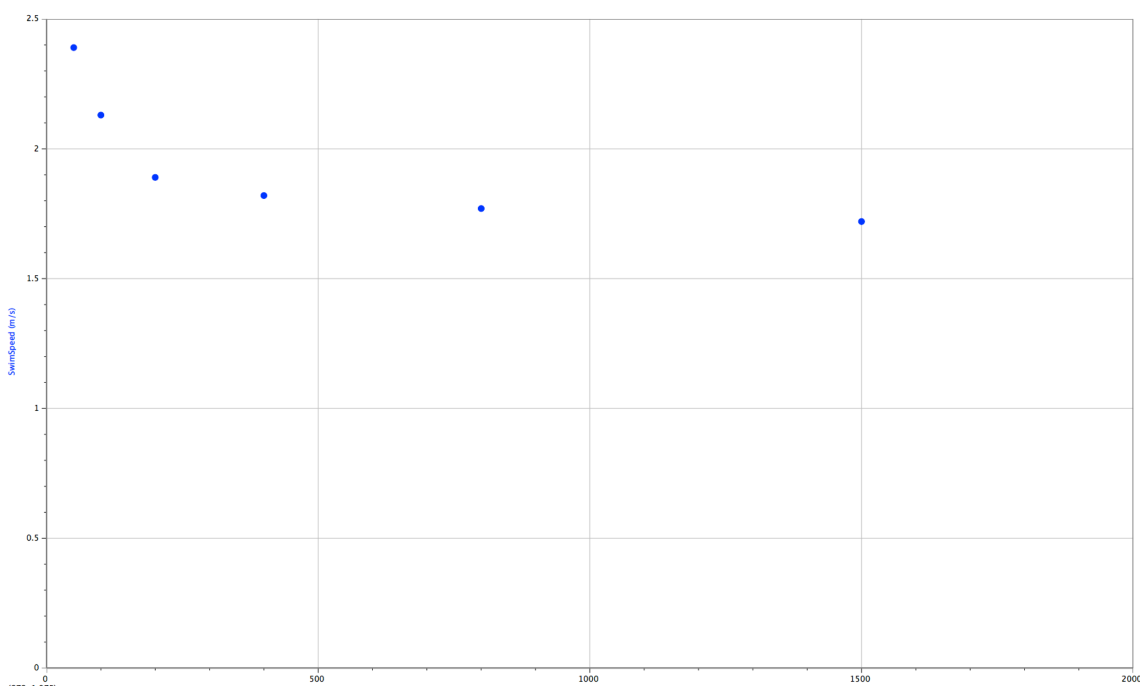
<u>Answers:</u>

a.  2.39 meters per second
b.  2.13 meters per second
c.  1.89 meters per second
d.  1.82 meters per second
e.  1.77 meters per second
f.  1.72 meters per second

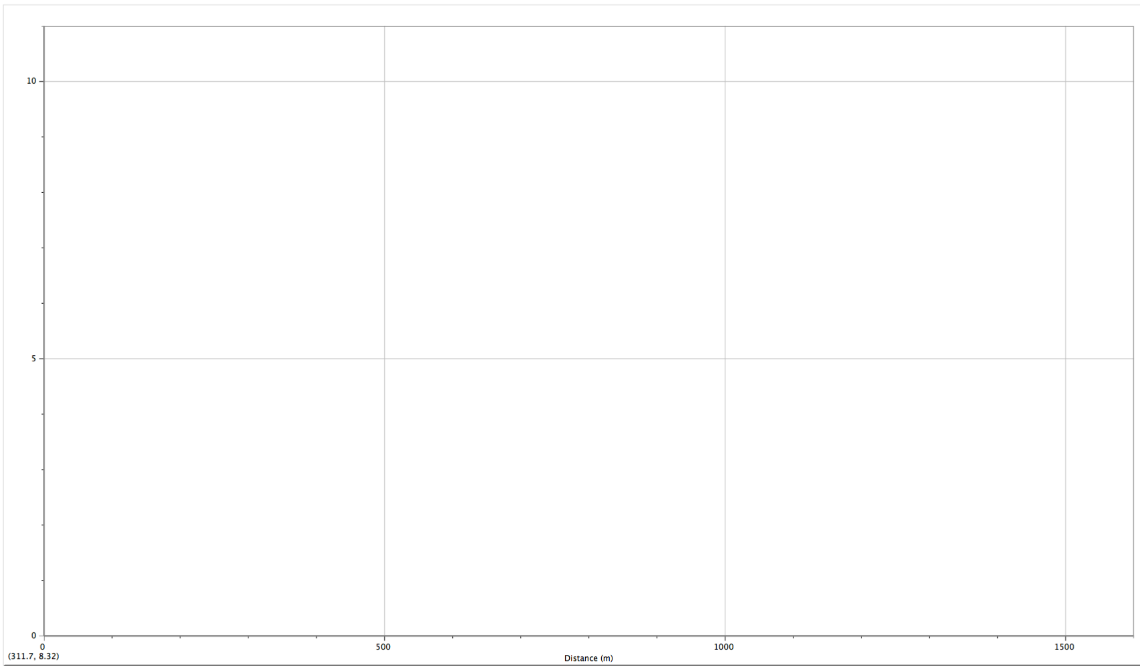
14. Plot the average speeds vs. race distance for the swimming race data of problem #11.



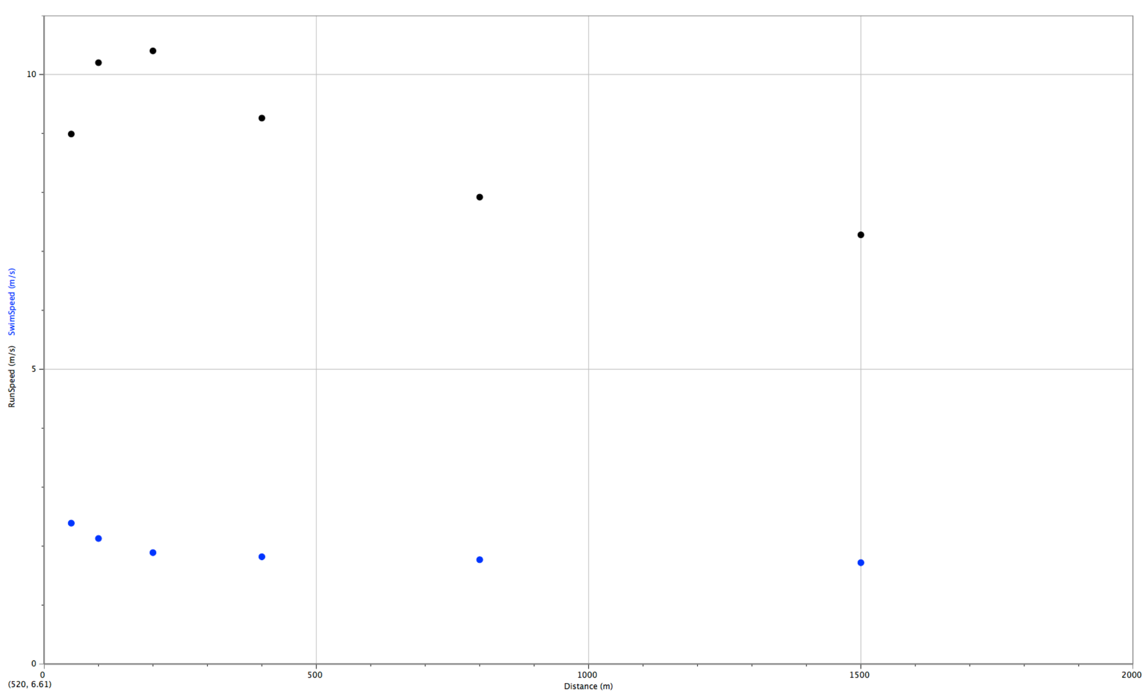

Answer:



15. Plot the average speeds vs. race distance for the swimming and running race data of problems #11 and 13. Scale the distances so that only races from 0-1600 meters are plotted.




Answer:



16. Based on the plot generated for problem #13, discuss the similarities and differences between the swimming and running results.

17. In women's fast pitch softball, speeds can reach ~120 kilometers per hour. The distance from the pitching mound to batter's box is 43 feet (13.11 meters). How long does it take a fast pitched softball to reach home plate?

_______________ second

Answer: 0.39 second

18. A served tennis ball travels ~60 feet (~18.5 meters) from the server's racket to the opposite court. Assuming a tennis ball is served at 150 miles per hour (~250 kilometers per hour) (among the fastest recorded), how long does it take the ball to land in the opposing court?

_______________ second

Answer: 0.27 second

19. In hurling, a hurler takes a penalty shot from a line 20 meters from the goal. Assuming the hurler hurls the sliotar at a speed of 150 kilometers per hour (93 miles per hour), how long does the goalkeeper have to block the shot?

_______________ second

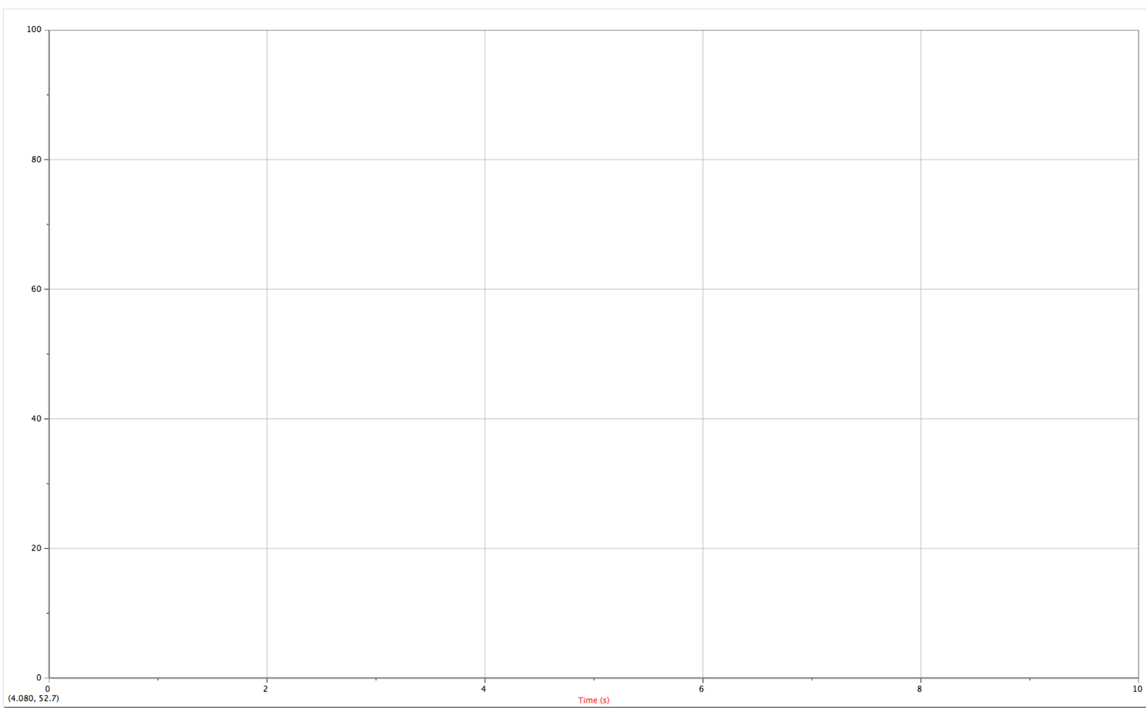
Answer: 0.48 second

20. Below is presented the times at 10 meter intervals for Bolt's world record 100 meter dash at the 2009 Track and Field World Championships held in Berlin.

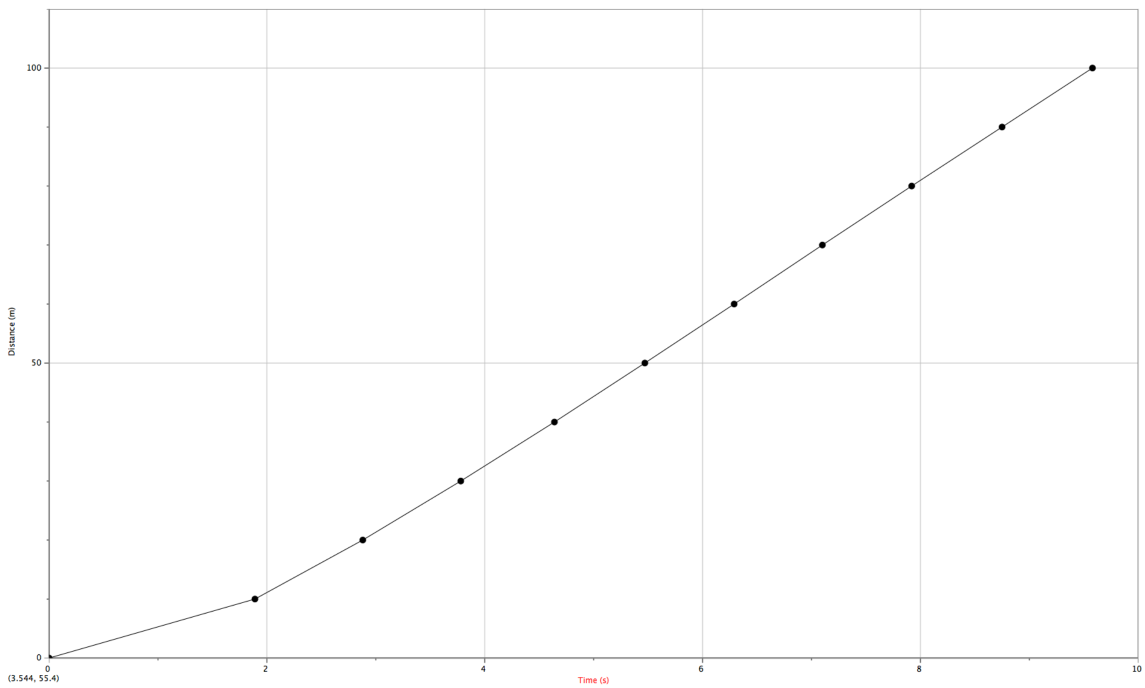
Source:
http://berlin.iaaf.org/mm/document/development/research/05/31/54/20090817073528_httppostedfile_analysis100mmenfinal_bolt_13666.pdf

| Distance (m) | Time (s) |
|---|---|
| 0 | 0 |
| 10 | 1.89 |
| 20 | 2.88 |
| 30 | 3.78 |
| 40 | 4.64 |
| 50 | 5.47 |
| 60 | 6.29 |
| 70 | 7.1 |
| 80 | 7.92 |
| 90 | 8.75 |
| 100 | 9.58 |

Plot this data with distance as the vertical axis and time as the horizontal axis.



Answer:




21. Below is presented the times at 10 meter intervals for Bolt's word record 100 meter dash at the 2009 Track and Field World Championships held in Berlin. Fill in the table for the average speeds over each interval.

| d (m) | t (s) | Split t (s) | Avg. Speed (m/s) |
|---|---|---|---|
| 0 | 0 | | |
| 10 | 1.89 | 0.445 | |
| 20 | 2.88 | 2.385 | |
| 30 | 3.78 | 3.33 | |
| 40 | 4.64 | 4.21 | |
| 50 | 5.47 | 5.055 | |
| 60 | 6.29 | 5.88 | |
| 70 | 7.1 | 6.695 | |
| 80 | 7.92 | 7.51 | |
| 90 | 8.75 | 8.335 | |
| 100 | 9.58 | 9.165 | |

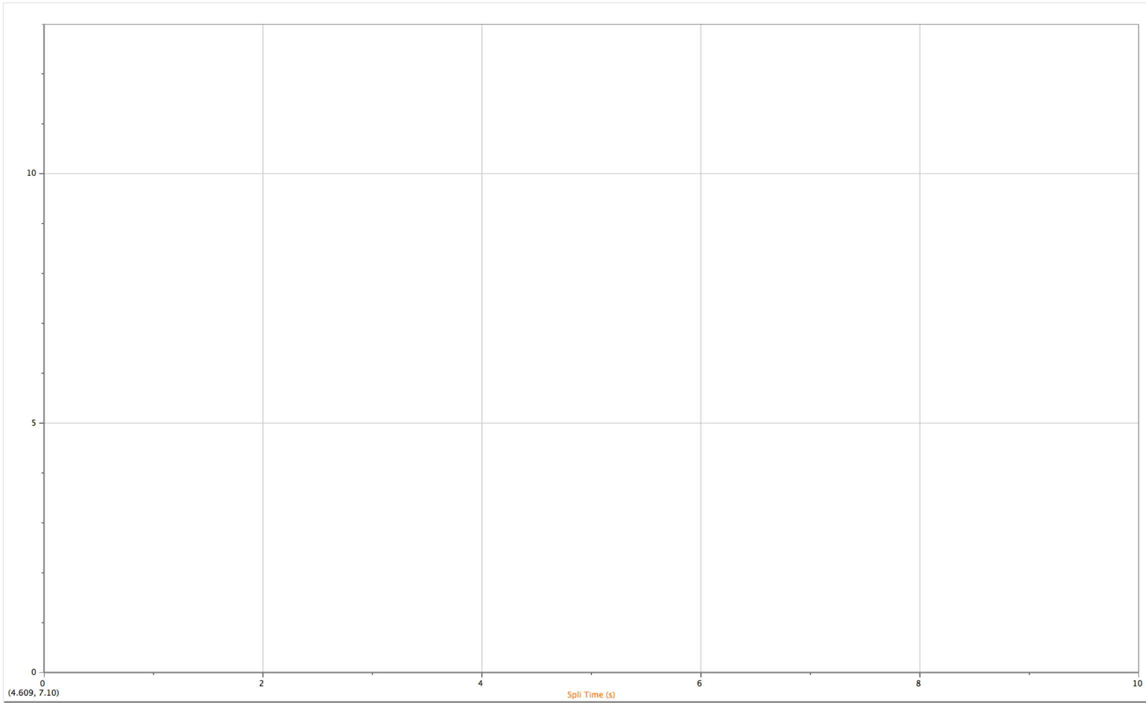
Answer:

| d (m) | t (s) | Split t (s) | Avg. Speed (m/s) |
|---|---|---|---|
| 0 | 0 | | |
| 10 | 1.89 | 0.445 | 5.29 |
| 20 | 2.88 | 2.385 | 10.1 |
| 30 | 3.78 | 3.33 | 11.11 |
| 40 | 4.64 | 4.21 | 11.63 |
| 50 | 5.47 | 5.055 | 12.05 |
| 60 | 6.29 | 5.88 | 12.2 |
| 70 | 7.1 | 6.695 | 12.35 |
| 80 | 7.92 | 7.51 | 12.2 |
| 90 | 8.75 | 8.335 | 12.05 |
| 100 | 9.58 | 9.165 | 12.05 |

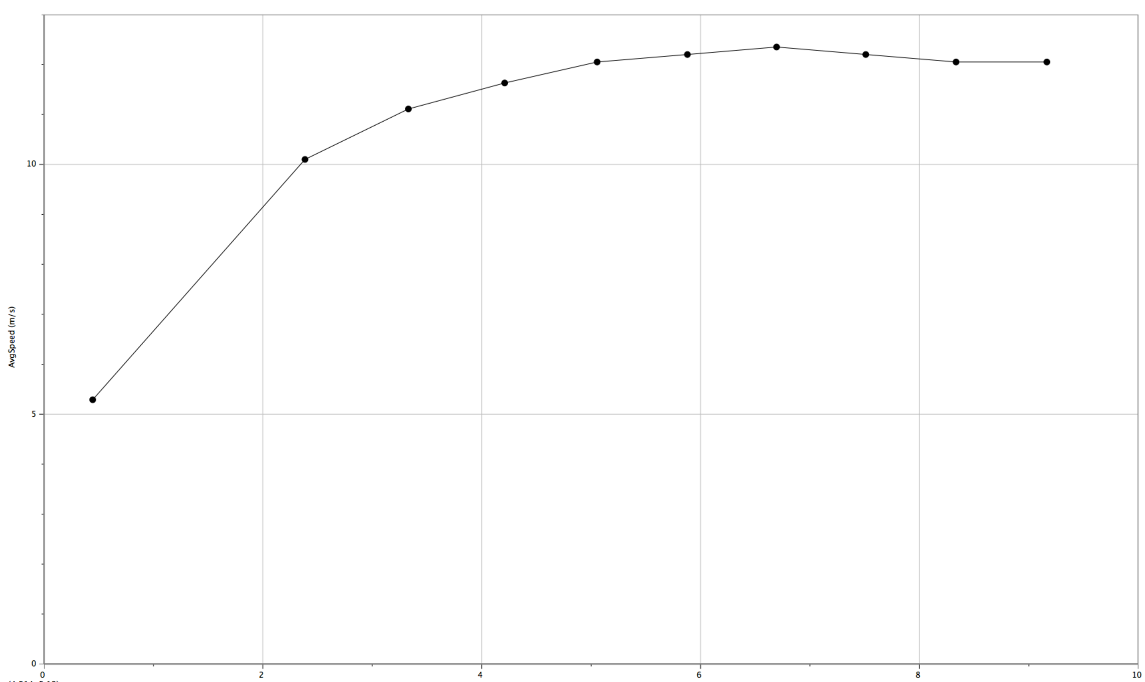
22. Compare the average speeds at the start and end of the race to the speeds we had obtained for Bolts' Olympic race in Chapter 1. Discuss the differences.

Answers: start: 7.5 m/s vs. 5.29 m/s; finish: 9.0 m/s vs. 12.05 m/s

23. Plot the data from Problem #19 with average speed as the vertical axis and split time as the horizontal axis.


10
5
0
0
2
4
6
8
10
(4.609, 7.10)
Spli Time (s)

Answer:


AvgSpeed (m/s)
10
5
0
0
2
4
6
8
10
(4.514, 5.13)
SplitTime (s)

24. From the data plotted in Problem #21, comment on the acceleration of Bolt during his race and find the average acceleration at the beginning of the race using the first 2 data points.

______________ $m/s^2$

Answer: 2.48 $m/s^2$

25. Many swimming records are broken into 2 categories: "long course" in which the event is held in a pool with 50 meter lanes, and "short course" with 25 meter lanes. Let's look at the differences:

Long Course
50 meter swimming freestyle (Cesar Cielo of Brazil in 2009)
Race time = 20.91 seconds

100 meter swimming freestyle (Cesar Cielo of Brazil in 2009)
Race time = 46.91 seconds

200 meter swimming freestyle (Paul Biedermann of Germany in 2009)
Race time = 1 minute and 46 seconds

400 meter swimming freestyle (Paul Biedermann of Germany in 2009)
Race time = 3 minutes and 40.07 seconds

800 meter swimming freestyle (Zhang Lin of China in 2009)
Race time = 7 minutes and 32.12 seconds

1500 meter swimming freestyle (Sun Yang of China in 2011)
Race time = 14 minutes and 34.14 seconds

Short Course
50 meter swimming freestyle (Roland Schoeman of South Africa in 2009)
Race time = 20.30 seconds

100 meter swimming freestyle (Amaury Leveaux of France in 2008)
Race time = 46.91 seconds

200 meter swimming freestyle (Paul Biedermann of Germany in 2009)
Race time = 1 minute and 39.37 seconds

400 meter swimming freestyle (Paul Biedermann of Germany in 2009)
Race time = 3 minutes and 32.77 seconds

800 meter swimming freestyle (Grant Hackett of Australia in 2001)
Race time = 7 minutes and 23.42 seconds

1500 meter swimming freestyle (Grant Hackett of Australia in 2001)
Race time = 14 minutes and 10.10 seconds

Now fill in the table below and calculate the long/short time ratios.

| Distance (m) | Long Course Time (s) | Short Course Time (s) | Ratio: Long/Short |
|---|---|---|---|
| 50 | | | |
| 100 | | | |
| 200 | | | |
| 400 | | | |
| 800 | | | |
| 1500 | | | |

<u>Answer:</u>

| Distance (m) | Long Course Time (s) | Short Course Time (s) | Ratio: Long/Short |
|---|---|---|---|
| 50 | 20.91 | 20.30 | 1.03 |
| 100 | 46.91 | 44.94 | 1.04 |
| 200 | 102 | 99.37 | 1.03 |
| 400 | 220.07 | 212.77 | 1.03 |
| 800 | 452.12 | 443.42 | 1.02 |
| 1500 | 874.14 | 850.1 | 1.03 |

26. Describe and account for the differences in long vs. short course swimming records as presented in problem #23.

<u>"Probable" answer</u>: The more frequent push offs from the ends of the pool may aid the short course swimmers.

27. A 90 mph fastball takes ~0.45 second to reach home plate from the pitcher's mound.
a. How long will it take a 60 mph knuckleball to reach home plate?

_______________ second

Answer: 0.675 second

b. Discuss the differences in terms of reaction time and the time to swing the bat.

# CHAPTER 10: Sports on the Moon

Earth as seen from the Moon

https://nssdc.gsfc.nasa.gov/imgcat/hires/a11_h_44_6552.gif

VIDEO 10.1: Golf on the Moon

https://digitalcommons.uri.edu/physicsofsports/48/

Select and watch VIDEO 10.1.

Sometime in the future I believe that mankind will colonize the Moon, at least as a base for scientific research and exploration and as a launch point for travel to more distant destinations in space. I expect that not too long after that happens the colonizers will engage in various fitness and sports activities, eventually getting more organized and playing team sports as well.

Based on what we have learned so far about the physics of sports in this book, I thought it would be interesting to consider how various sports would be affected if they were played on the moon. That's the subject of this chapter.

Now in spite of the video you watched at the beginning of this chapter (allegedly an attempt to hit a golf ball on the Moon), I'm going to assume that space suits and breathing apparatuses are not an issue in affecting sports performances (though they certainly would be now!). I imagine that space equipment will evolve to be much lighter and less cumbersome. So let's not worry about that here. Also, I will assume that sports that are normally played outdoors on Earth (football, baseball, skiing, soccer, rugby, golf, ...) will still be played outside on the Moon and those typically indoor sports (basketball, ping pong, bowling, swimming, diving, ...) will be played in some sort of enclosed stadium (with air in it). There are many other sports that are played indoors or outdoors (hockey, track and field, ...) that we'll deal with as they come up.

So Earth vs. Moon, what are we dealing with? Two important differences as far as sports are concerned. What are they?

QUIZ 10.1

What are the two most important sports-related differences between the Earth and the Moon?

( ) Gravity is greater on the Moon and the air is less dense.
( ) Gravity is less on the Moon and the air is less dense.
( ) Gravity is greater on the Moon and there is no air.
( x ) Gravity is less on the Moon and there is no air.
( ) Gravity is greater on the Moon, the air is denser.
( ) Gravity is less on the Moon and the air is denser.

Hopefully you chose correctly. With no air, some sort of space suit is needed for breathing purposes and to provide air pressure for the astronauts. As we have mentioned in previous chapters, the force of gravity is 6 times less on the Moon than on Earth.

With these two factors in mind, let's begin our discussion and analysis.

## 10.1: Vertical Motion

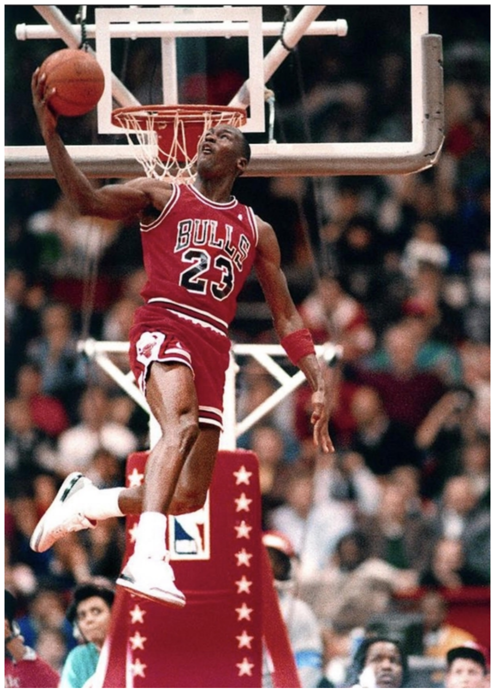



FIGURE 10.1
A Dunk by Michael Jordan

https://cdn-blog.scorum.com/production/thesportsguru/f84ad34f493c60fc_800

You've probably seen some impressive dunks if you have watched any professional basketball games. What would be different about a basketball game and in particular a dunk if the game were played on the Moon (in an enclosed, sealed stadium so "air" is not an issue)? First, we need to review what we learned about mass and weight.

QUIZ 10.2

On earth, Michael Jordan's mass and weight were (when he was playing) approximately 100 kilograms and 1000 Newtons, respectively. What about on the Moon.

a. What would Michael's approximate mass be on the moon:

( ) 17 kilograms
( ) 33 kilograms
( x ) 100 kilograms
( ) 300 kilograms
( ) 600 kilograms

b. What would Michael's approximate weight be on the moon:

( x ) 170 Newtons
(   ) 330 Newtons
(   ) 1000 Newtons
(   ) 3000 Newtons
(   ) 6000 Newtons

I hope that you recalled that mass is a measure of the "amount" of an object and does not change when the object is subjected to forces including gravity. Weight, on the other hand, is the force due to gravity so if the gravitational force on the Moon is 1/6 that on Earth, the weight will also be 1/6 the weight on Earth. W = m*g* still but with *g*~1.6 $m/s^2$ on the Moon.

With a reduced weight on the Moon, how will the jumping ability of Michael Jordan or you if you become a Moon colonizer be affected?

QUIZ 10.3

Compare Michael's jumping ability on the Earth vs. the Moon.

( x ) Jordan should be able to jump higher on the Moon.
(   ) Jordan should only be able to jump to a lower height on the Moon.
(   ) Jordan should be able to jump to the same height on the Moon.

I hope that you realized that with reduced gravity on the Moon, anyone should be able to jump higher. But how much higher? Since the Moon's gravity is 1/6 that of earth, does that mean that you would be able to jump 6 times higher? Let's figure it out.

We're assuming a straight, vertical jump from rest. You push off giving your body some initial speed. Your body rises up to a greater height than on Earth.

QUIZ 10.4

You jump up and reach your highest point when what happens?

(  ) Your acceleration goes to 0.
(  ) Your acceleration equals your speed.
( x ) Your speed goes to 0.

This is review so hopefully you chose the correct answer.

We'll proceed with our analysis by considering the Conservation of Energy that we learned about in Chapter 5.

QUIZ 10.5

a. Just when you have finished pushing up from the floor with an initial speed, v, what is your primary form of energy:

( ) Gravitational Potential Energy
( x ) Kinetic Energy
( ) Elastic Energy
( ) Thermal Energy due to Friction

b. When you have reached the highest point in your jump, what is your primary form of energy:

( x ) Gravitational Potential Energy
( ) Kinetic Energy
( ) Elastic Energy
( ) Thermal Energy due to Friction

Did you get these right? I hope so. By Conservation of Energy, these two forms of energy (Kinetic Energy at the bottom and Gravitational Potential Energy at the top) should be approximately equal. Making use of Equations 5.1 and 5.3 for those forms of energy, and setting them equal yields the following relationship:

$$\frac{1}{2}mv^2 = mg_{moon}h$$

If we cancel the mass and solve for the height, we get:

$$h = \frac{v^2}{2g_{moon}}$$

This tells us that since the acceleration on the Moon is 1/6 that on Earth, the height of the jump should be 1/(1/6) = 6 times greater on the Moon than on Earth assuming the same take-off speed. That will make dunking a basketball quite easy on the Moon. Even I could do it!

Now one thing we didn't nail down is: what height? Specifically, what height do we use in the equation above? When we were considering height changes of extended objects (like human bodies) what was the "height" that mattered?

QUIZ 10.6

To calculate height changes of extended objects such as a human body in terms of energy changes, etc., what was the "height" that was important? (Hint, see section 6.6.)

| | |
|---|---|
| ( ) | The top of an object |
| ( ) | The bottom of on object |
| ( x ) | The center of mass of an object |

It is the center of mass that matters so what we really are concerned with is the change in height of the center of mass during a jump. Michael Jordan's height is about 2 meters so his center of mass at about waist level is approximately 1 meter off the ground (when he is standing upright). A basketball net rim (on Earth!) is at a height of 10 feet, ~3 meters. Take a look at Figure 10.1 above and estimate how close to the rim is Michael's center of mass as he goes for the dunk.

QUIZ 10.7

What is the approximate height difference between Michael's center of mass and the basketball rim in Figure 10.1?

| | |
|---|---|
| ( ) | 0 |
| ( x ) | 1 meter |
| ( ) | 2 meters |
| ( ) | 3 meters |

1 meter is a good estimate. That means that his center of mass increased from a height of ~1 meter before his jump to ~[(3 meters for the height of rim) - (1 meter for the height of the center of mass below rim)] = ~2 meters. So the *increase in height* of his center of mass was ~1 meter. That means that on the Moon he should be able to increase his center of mass height by ~6 meters, 5 meters greater than on Earth. In terms of dunking the basketball, the rim would have to be placed ~5 meters higher - a height of ~8 meters (~26 feet) to expect to see a dunk of comparable difficulty. Make sense?

For any sports projectile the same basic analysis applies. All other things being equal (are they? probably not) projectiles thrown straight up into the air will travel to heights approximately 6 times greater than their heights on Earth.

One of the only "projectiles" that travels in a more or less vertical trajectory that we have considered previously is a diver stepping off a diving board. What will be different on the Moon?

## QUIZ 10.8

A diver steps off a diving board on the Moon. What will be different than on Earth? (Hint: remember that the acceleration due to gravity is 6 times less on the Moon.)

( ) The diver will hit the pool surface on the Moon at a greater speed than on Earth.
( x ) The diver will hit the pool surface on the Moon at a lesser speed than on Earth.
( ) The diver will hit the pool surface on the Moon at the same speed than on Earth.

Since the acceleration is less on the Moon, the change in speed and the final speed will be less. How much less - 6 times? No, not in this case. We can show by Conservation of Energy or by kinematic equations that the final speed of the diver entering the water on the Moon should be $\sqrt{6} = 2.4$ times less. For a step off a 10 meter dive platform, the speed on Earth will be ~14 m/s upon entering the water; on the Moon, ~5.8 m/s. Should the diving platforms be raised? What do you think? What about the *time* it takes the diver to hit the water?

We can see this affect in action - an object falling straight down on the Moon - by examining a classic (in physics that is) video taken during one of the first Moon landings. Astronaut Dave Scott on the Apollo 15 mission simultaneously dropped a hammer and a feather. Answer the following question and then click on VIDEO 10.2
to see if you are correct.

## QUIZ 10.9

When astronaut Dave Scott simultaneously dropped a hammer and a feather on the Moon, which object hit the ground first? (Hint: Think which would hit the ground first on Earth and what is different about the Moon vs. the Earth.)

( ) The hammer
( ) The feather
( x ) Both objects should hit the ground at the same time.

Let's find out. Select and watch VIDEO 10.2.

VIDEO 10.2: Hammer-Feather Drop on the Moon

https://digitalcommons.uri.edu/physicsofsports/49/

I hope you realized since there is no air on the Moon and therefore no air resistance, that both objects should hit the ground at the same time, and they did!

Showing the effects of lack of air resistance - that all objects fall at the same rate - was the main purpose of that demonstration, but we can also learn something by considering the *time* of the falls. Let's assume that the hammer and feather were dropped from a height of ~1 meter (that looks about right from the video). If we use a kinematic equation we can find the time it takes an object to hit the ground. On Earth that turns out to be ~0.45 second. As we would predict for diving on the Moon, the time for the hammer and feather should be greater on the Moon. But how much greater? Run the video again and measure the time as best you can.

VIDEO QUIZ 10.10

How long did it take the hammer and feather to hit the ground?

______________ seconds

(Answer: 1.1 seconds)

Multiplying 0.45 second by the factor of 2.4 discussed above gives a time of ~1.1 seconds. Is that close to the time you measured?

## 10.2: Projectiles

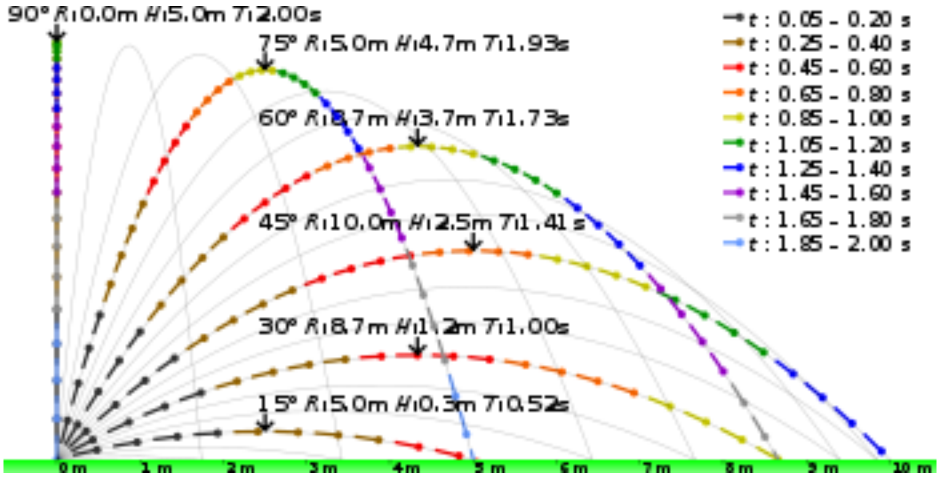



FIGURE 10.2: Trajectories of projectile vs. launch angle

http://upload.wikimedia.org/wikipedia/commons/thumb/6/61/Ideal_projectile_motion_for_different_angles.svg/350px-Ideal_projectile_motion_for_different_angles.svg.png

To examine two-dimensional motion on the Moon (which usually involves the motion of some kind of projectile), let's take a look at the shotput. I'll assume this is another outdoor event so air is not an issue, just the reduced gravity.

One of the important points we discussed regarding two-dimensional motion in Chapter 2 was the ability we have to separate out vertical and horizontal motion, combining them later as needed. First, what about the horizontal component of motion? How will that be affected on the Moon?

QUIZ 10.11

Assuming a shotput competition is held outdoors on the Moon, there will be no air resistance. What force or forces act on the shot in the *horizontal* direction?

( ) Weight
( ) Tension
( ) Normal Force
( ) Friction
( x ) There are no forces in the horizontal direction.

Hopefully you chose correctly. In the absence of air resistance, the only force acting on a projectile once it is "launched" is the force of gravity (the object's weight) which acts strictly in the vertical direction. So no force means no acceleration means constant velocity in the horizontal direction, just as we had determined in Chapter 2 for projectiles launched on Earth (we were ignoring air resistance at that point). Basically, almost no difference on the Moon.

Now let's talk about the vertical motion. From the previous section you should have some understanding of the Moon-induced effects on strictly vertical motion. The same rules apply to the vertical component of two-dimensional motion such as the trajectory of a shot. The force of gravity is less on the Moon so the vertical motion will be modified. We already learned that projectiles launched in a strictly vertical direction will attain a height ~6 times that on Earth for the same initial speed. This applies to the vertical component of two-dimensional motion as well. So the maximum height of the trajectory of a two-dimensional projectile will be ~6 times the height on Earth.

Another parameter we discussed in Chapter 2 with regards to two-dimensional motion was the "Range" of the projectile, the horizontal distance it travels before it hits the ground. In Figure 2.10, reproduced at the beginning of this section, is displayed the trajectories of projectiles launched at various angles assuming no air resistance (which works even better for the Moon than on Earth). The maximum range is at an angle of 45$^{o}$. (This assumes that the starting and ending heights were the same, which would <u>not</u> be the case in many sports situations.) Will the range be different on the Moon? "Yes" is the answer.

But why would the range be different on the Moon since we just decided that the horizontal motion will be more or less unchanged? To understand this affect we must recall that it is not just horizontal speed that determines the range but also how long the projectile is in the air. (Not "in the air" for the Moon; let's say "in flight").

QUIZ 10.12

On the Earth or the Moon, if a projectile is in flight for a longer time, how will the range be affected?

( ) The range will be the same.
( x ) The range will be greater for the greater time.
( ) The range will be less for the greater time.

I hope that it is clear that if a projectile remains above the surface for a greater time, then it will travel a greater distance before landing - a greater range.

QUIZ 10.13

Therefore, compare the range of a projectile on Earth to the range on the Moon.

( ) The range on the Moon will be the same as the range on Earth.
( x ) The range on the Moon will be greater than the range on Earth.
( ) The range on the Moon will be less than the range on Earth.

Putting it all together: on the Moon, the time in flight will be greater so the horizontal distance traveled before landing (the range) will be greater than on the Earth. But by how much? Utilizing again various kinematic equations, it is not difficult to show that the range of a projectile is <u>inversely proportional to the acceleration due to gravity</u>. On the Moon, $g_{moon}$ is ~1/6 that of Earth so the range of a projectile on the Moon will be ~6 times the range on Earth (and in addition with no air resistance either.) We can also see this as follows: the time in flight on the Moon is 6 times greater; horizontal distance is simply speed times time. Therefore, again the range on the Moon is 6 times greater.

Let's now apply this knowledge to some sports. First, the shotput. The current world record for the shotput is 23.12 meters (~79 feet) (set by Randy Barnes from the U.S. in 1990 - very impressive, I think, that that record has held up for more than 20 years). Assuming everything else is the same, we can predict a "Moon record" for the shotput of ~6 x (23.12) meters ~139 meters (~455 feet! - the range of a well-hit home run in baseball on Earth). In addition, in Chapter 8 we claimed that 1/2 foot was lost (out of 70 feet) to air resistance. That would make the Moon record a little bit greater, but not by much.

What other relevant sports did we consider? We talked about the discus in Chapter 8. The current world record for the discus is 74.08 meters (~243 feet) (Jurgen Schult from Germany set in 1986). By the same reasoning, we would predict a "Moon record" of ~444 meters (~1460 feet! - how many football field lengths is that?). Or would we? Not quite (why not?) - see the discussion in Section 10.5.

Likewise, baseballs, footballs, and soccer balls would be kicked further, golf balls would be hit further, the long jump would be much longer, and the list goes on. I think we would want to modify some of these sports. Some of these distances are out of control!

## 10.3: Force and Energy

FIGURE 10.2
Steve Hooker of Australia in a pole vault competition

http://www.flickr.com/photos/cooldogphotos/2840070128/

Another example of a two-dimensional projectile in sports which in this case involves almost vertical motion is the pole vault which we discussed in Chapter 5. Recall that the energy in this event changed from kinetic energy (the vaulter during the approach) to elastic energy (bent pole during the take-off and swing-up) to gravitational potential energy (maximum height of the vaulter). The ability of a pole to bend or store elastic energy will not in any way be affected by being on the moon. Therefore, if the vaulter can obtain the same kinetic energy as he or she would on earth (and that's a big if that we will discuss later) then the vaulter should benefit from the same increase in height (a factor of ~6) that we have discussed in the previous sections.

The world record for the pole vault is ~6 meters (actually 6.15 meters: set by Sergey Bubka of the Soviet Union/Ukraine). By the same analysis we used for the dunk in basketball, that is ~5 meters above the center of mass of the vaulter, so we should expect an increase in height by 6 x (5 meters) = 30 meters. Pole vault records on the moon should therefore reach ~(30 meters) + (1 meter-center of mass height) = 31 meters (~102 feet). Wow!

However, in addition to the big "if" we will discuss later concerning kinetic energy, I do see another problem facing the Moon's pole vaulters. Check out the figure of Steve Hooker above. What about the pole?

QUIZ 10.14

Approximately how long is Steve Hooker's pole in Figure 10.2?

| | |
|---|---|
| ( ) | 2 meters |
| ( ) | 4 meters |
| ( x ) | 6 meters |
| ( ) | 8 meters |

You noticed, I hope, that the pole is almost as long as the bar is high (~6 meters). That means that to clear a bar at a height of 31 meters, the vaulter would need a pole with a length of at least ~30 meters (~98 feet). That is a very long pole to be running with on the approach. It wouldn't be the weight of the pole since that would be the same as on Earth (~6 times longer but gravity is ~6 times less) but the fact that the pole must be quite flexible. Could you keep a 30 meter long flexible pole from touching the ground on the approach and also aim it properly before take-off? Not easy! In addition, could the pole bend enough without breaking at that length? So there are some problems and maybe some new challenges in pole technology to deal with. I'm going to suggest that a 31 meter Moon pole vault record is not going to happen! Maybe you'll be around in the future to find out.

The high jump that we considered in Chapter 6 is another example of a projectile (the athlete) in which the goal is to maximize the height. As for the pole vault, if the high jumper could attain the same kinetic energy before his take-off, the Moon high jump record should be ~6 times greater than the world record (in terms of the center of mass change), which currently is 2.45 meters (~8 feet) set by Javier Sotomayor of Cuba in 1993. That would make the Moon record ~32 feet!

FIGURE 10.3: Brian Shaw of the U.S. in the Atlas Stone event of the World Strongest Man competition

https://www.flickr.com/photos/tvnewsphoto/2858679026/

In Chapter 4 we looked at several events from the World's Strongest Man competitions. How about the Moon's Strongest Man competition? What would be different? Let's consider the Atlas Stones event as pictured above. The competitors must lift 5 stones with masses varying from 100 to 160 kilograms and place them on pedestals with heights of ~2 meters in the shortest amount of time. How will the same event compare in the Moon's Strongest Man competition?

QUIZ 10.15

Compare the Atlas Stones event on the Earth and the Moon.

( x ) The event will be "easier" on the Moon.
(   ) The event will be "harder" on the Moon.
(   ) The event will be the same on the Moon.

Even though the *mass* of the stones would be the same on the Earth as on the Moon, the *weight* of the stones would be ~6 times less on the Moon. The Atlas Stones event, if left unchanged would not be nearly as much of a challenge. Let's pick out a particular stone and compare.

QUIZ 10.16

On the Moon, what would be the weight of a 120 kilogram Atlas Stone?

(   ) 100 Newtons
( x ) 200 Newtons
(   ) 300 Newtons
(   ) 600 Newtons
(   ) 900 Newtons
(   ) 1200 Newtons

QUIZ 10.17

What mass on Earth has the same weight as the weight of a 120 kilogram Atlas Stone on the Moon?

(   ) 10 kilograms

( x ) 20 kilograms
(   ) 30 kilograms
(   ) 40 kilograms
(   ) 60 kilograms
(   ) 120 kilograms

I hope these last two quizzes were just review for you. A weight of 200 Newtons is ~44 pounds. Even I could pick up a stone with that weight and "maybe" place it on a 2 meter pedestal. Clearly this event has to be modified.

Now it is not just force (weight of stones) that matters in this competition but also the height to which they are lifted. This combination of force times distance is the work. So the work also will be ~6 times less on the Moon. To make the work comparable to the competition on Earth we could increase the weight (by increasing the mass) of the stones by a factor of 6 or we could increase the height of the pedestals by a factor of 6 (with stairs or a ladder included!), or some combination of both. If you were on the Moon's Strongest Man planning committee, which would you recommend?

## 10.4: Running

I made some comments earlier about an "if" involving the kinetic energy of a pole vaulter on the Moon. In this section I want to explain what I mean by that. To do that let's consider running a 100 meter race on the Moon. In Chapter 1, we examined Usain Bolt's gold medal world record-setting performance at the 2008 Olympic Games.

Bolt ran 100 meters in slightly less than 10 seconds (9.69 seconds). We calculated that his average speed was ~10.3 meters/second. We can also calculate his "sort of " average acceleration using another kinematic equation. Using that distance and time and assuming the acceleration was constant throughout the race (not a good assumption) we obtain an acceleration of ~2 m/s$^2$. This may not seem that great as compared say to the acceleration of gravity (on Earth) of ~10 m/s$^2$. While that is some measure of his average acceleration, is that the number that best reflects his running ability? I say we can do better.

To accelerate during his race, a force must be involved. Some force is pushing Bolt forward. What is it?


FIGURE 10.4: Usain Bolt of Jamaica in his final race (he won a bronze medal)

https://aleteiaen.files.wordpress.com/2017/08/web3-usain-bolt-runner-olympics-olympian-gold-jamaica-shutterstock.jpg?quality=100&strip=all&w=620&h=310&crop=1

QUIZ 10.18

Examine the figure above and decide on the force that is accelerating Bolt forward:

| | |
|---|---|
| (   ) | Weight |
| (   ) | Tension |
| (   ) | Normal Force |
| ( x ) | Friction |
| (   ) | Lift Force |

Bolt pushes on the track and the track pushes back on Bolt by way of the frictional force. (Another example of which of Newton's Laws?) What kind of friction is involved in this process?

QUIZ 10.19

What kind of friction between running shoe and track surface is involved in a typical run? (Hint: the runner is moving but is he or she *sliding*?)

| | |
|---|---|
| ( x ) | static friction |
| (   ) | kinetic friction |

Static friction it is. In general no or very little sliding is involved.

So static friction is the primary force that causes the runner to accelerate forward. But is friction acting the entire time of the run (~10 seconds for Bolt's 100 meter sprint)? Take a look at another photo of Bolt during a race and you decide.

FIGURE 10.5: Usain Bolt of Jamaica in the 200 meter finals at the 2008 Summer Olympic Games

https://talksport.com/wp-content/uploads/sites/5/2016/08/ubnolt.jpg?strip=all&w=700

QUIZ 10.20

From an examination of the photo above, what can we conclude about the frictional force acting on Usain Bolt?

( ) The frictional force is acting on Bolt throughout his race.
( x ) The frictional force is only acting on Bolt during a portion of his race.

I hope it is clear from the figure above that Bolt and most runners will spend some of their running time "in flight", not touching the ground. Whenever that is the case, obviously he is not pushing on the ground so the frictional force on Bolt goes to 0.

Let's now estimate how much of the time a runner spends actually in contact with the ground. In the video you will watch next (VIDEO 10.3), a world class sprinter, Asafa Powell, also from Jamaica, was captured in slow motion. Select VIDEO 10.3 and watch his slow motion run. What I want you to record is the approximate number of frames in a single stride (foot down on the track to the next step) and the number of frames in which his foot is actually in contact with the ground. Of course, these will be estimates, but do your best.

VIDEO 10.3: Sprinter Asafa Powell of Jamaica in Slow Motion

https://digitalcommons.uri.edu/physicsofsports/50/

QUIZ 10.21

a. For how many frames was Powell's foot in contact with the track during a single stride?

______________ frames

(Answer: 90 frames)

b. How many frames were there in a single stride?

______________ frames

(Answer: 50 frames)

I got 90 frames and 50 frames respectively, which again is just an estimate. Were your numbers close to mine?

This result says that Powell is in contact with the ground ~50% of the time so the frictional force will only act for that length of time at most. Let's assume that this analysis applies to Bolt's 100 meter sprint as well. This means that he is only accelerating for 5 seconds out of the 10 seconds of the race. Using this new number and a kinematics equation yields an ~average acceleration of ~8 $m/s^2$ (during the time he is in contact with the ground and is actually accelerating) instead of the 2 $m/s^2$ we found earlier.

What does this have to do with running on the Moon you are no doubt wondering? We're getting there!

With a few estimates and approximations in hand, we think that Bolt's average acceleration due to static friction was ~8 $m/s^2$. Now there is a limit to the amount of force that static friction can provide. In Chapter 4 we learned that the maximum value of static friction (for the simple case of a horizontal surface and no other vertical forces) is given by the weight of the object multiplied by the coefficient of static friction. For rubber on concrete (probably good enough for a running shoe on a track) this coefficient is equal to ~1. When we put this together with Newton's 2nd Law, F = ma, we get the following relationship for the *maximum* static frictional force and acceleration:

$$F = f_{\text{static-max}} = mg(1) = ma$$

where the "1" in the above is the coefficient of static friction for rubber on concrete.

Dividing the mass on each side we find that the maximum acceleration that can be attributed to static friction is $g$, which is ~10 $m/s^2$ on the Earth. That works out pretty well compared to the acceleration we estimated for Bolt's race (8 $m/s^2$). In fact, I'd say with all the uncertainties and approximations that Bolt's acceleration is pretty much the maximum allowed by friction. By the way, what would happen if Bolt tried to increase his acceleration significantly?

QUIZ 10.22

What would happen if Bolt tried to increase his acceleration significantly?

( ) He would run faster and set a new world record.
( x ) He would slip.

That's the idea behind the critical or maximum value of static friction. If this is exceeded, the frictional force will turn into kinetic friction which is generally less than maximum static friction. Kinetic friction means sliding or slipping.

Now we can finally take what we have learned to the Moon.

On the Moon, the acceleration due to gravity is only ~1.6 m/s$^2$. That means to me that for a race on the Moon with no other alterations in track or shoes or whatever (see below for some possible variations) that the maximum average acceleration that a runner could generate is ~1.6 m/s$^2$. This acceleration is significantly *less* than the maximum acceleration allowed on Earth or the acceleration we estimated for Bolt in his 100 meter sprint. The reduced weight on the Moon in fact does *not* assist a runner in speeding up but rather impedes a runner.

If we use this value of the acceleration during a 100 meter sprint and still assume that the acceleration applies approximately 50% of the time, then we come up with a 100 meter Moon record time of only ~24 seconds vs. ~10 seconds for Bolt's world record (dropping his average speed from ~10.3 m/s to ~4.2 m/s).

The situation on the Moon is even a little more complicated. If you recall the slow motion video of Powell's run, the angle that his foot makes with the ground changes significantly during the time the foot is in contact with the track. Certainly at least some of the time, part of the force of the foot will be directed towards the ground with the ground pushing back in the vertical direction. On the Moon, this push will cause the runner to lift off the track more so than on Earth, reducing the amount of time per stride the foot actually contacts the track surface and can accelerate the runner forward. I think this affect will further reduce the runner's speed though it is not clear exactly how all these factors will come together. At the very least I expect the Moon runner to modify his or her running style to push *back* as much as possible and not *down*.

Now you can see why I added a big "if" to the pole vaulting event on the Moon. If the vaulter cannot accelerate as much as on Earth, the vaulter will not have an equal amount of kinetic energy when he or she starts the take-off. Because of the reduced gravity, I still expect higher Moon records for the pole vault than on Earth, but not by a factor of 6. The same idea applies to the high jump, long, jump, and any other events requiring a running approach. Even throwing events such as discus, shot put, and javelin will be affected since they all involve some sort of running or spinning approach before the launch of the projectile. How much all of these Moon records will be affected I leave to you to think about.

Turning to other sports, I can see a similar issue even when no running is involved. Can a baseball batter on the Moon take the same swing at the ball without losing his feet? Can the golfer swing his club with as much power? Can the football quarterback throw a long pass? And more....

I think you can see that on the Moon a new set of skills will need to be developed to enable athletes to stay on their feet and/or to run as fast as possible in reduced gravity. One alternative could be to develop special shoes and playing surfaces with enhanced friction or that temporarily lock down the feet of the athlete during a golf swing for example. I could even imagine a special track that allowed the runner's feet to be locked down for an instant then released as he or she completes the stride. How do you think sports techniques and technology would evolve on the Moon?

## 10.5: Air and Water

In Section 10.2, I reported the current men's shotput and discus records as ~79 feet and ~243 feet, respectively. Multiplying these ranges by a factor of 6 would result in Moon records of ~455 feet for the shotput and ~1460 feet for the discus. But is this correct on the Moon? No. Why not? We need to recall why the records for these two projectiles are so different. The mass and weight of the discus is less than that of the shot (2 kilograms vs. 7.26 kilograms for the masses) but that is not the entire explanation. In Chapter 8 we learned that there is an additional force that extends the range of the discus. What is it?

QUIZ 10.23

What force extends the range of a properly-thrown discus?

( ) Weight
( ) Tension
( ) Normal Force
( ) Friction
( x ) Lift Force

Hopefully you recall the picture that when a discus is thrown at an angle, increased air pressure on the bottom gives it a lift.

QUIZ 10.24

How will the Lift Force on the Moon compare to Earth (assuming the discus event is an outdoor event)?

( ) The Lift Force on the Moon will be 6 times less than on Earth.
( ) The Lift Force on the Moon will be 6 times greater than on Earth.
( ) The Lift Force on the Moon will be the same as on Earth.
( x ) There will be no Lift Force on the Moon.

Obviously, no air on the Moon so no Lift Force. Therefore, the discus will travel further than the shot put because its mass is less (so the discus can be thrown with a greater initial speed), but the Moon discus record will not be 6 times that on Earth. (Likewise, the frisbee won't be as much fun to throw around on the Moon!)

Now with no air, there are some other forces we studied that will <u>not</u> play a role in sports on the Moon (outdoors). What are they?

QUIZ 10.25

What other force besides the drag force (air resistance) and lift forces will not exist on the Moon? (Check all that apply.)

( ) Weight
( ) Tension
( ) Normal Force
( ) Friction
( x ) Magnus Force

With no air, the entire discussion I made about Bernoulli's Principle and the Magnus Force due to the spin of a projectile is not relevant on the Moon. What does that mean with regards to sports? Golf balls and baseballs won't gain any lift from the Magnus Force so their range will be greater on the Moon than on Earth but not by a factor of 6. (No more hook shots or slices in golf either; I guess that's good?) And what about all the expense to develop the "perfect" dimpled golf ball? How will that work out on the Moon? Do we see the return of smooth golf balls?

Additionally, no more "Bend it like Beckham" soccer shots and no more breaking balls in baseball. The ball won't "curve" due to spin on the ball. That's not fun! And the slow, knuckleball won't dance around anymore. It will just be crushed!

FIGURE 10.6: Cliff Jumping

http://www.youtube.com/watch?v=t0GESlaVNdE

One more related issue. Think about the cliff jumpers we watched in Chapter 8. They jumped off the cliff and immediately started to accelerate from rest at a rate of ~10 $m/s^2$. But did this acceleration remain constant until they hit the ground? No. Why not?

QUIZ 10.26

What force besides the weight affected the acceleration of the cliff jumpers?

( ) Weight
( ) Tension
( ) Normal Force
( x ) Drag Force
( ) Magnus Force

The collisions with the air (air resistance or the drag force) provided a force in the opposite direction from their weight, thus causing the acceleration of the jumpers to decrease. If they traveled far enough (not clear in this particular jump) their acceleration would have gone to zero as they reached their terminal speed (~110 miles per hour).

How would cliff jumpers fare on the Moon? They jump off a cliff on the Moon and will immediately accelerate at ~1.6 $m/s^2$, 1/6 that of Earth. What happens later?

QUIZ 10.27

How would the terminal speed of cliff jumpers be affected on the Moon?

( ) The terminal speed would be 6 times greater on the Moon than on Earth.
( ) The terminal speed would be 6 times less on the Moon than on Earth.
( x ) There is no terminal speed on the Moon.

No air so no drag force so no change in acceleration so no terminal speed.

QUIZ 10.28

What happens when the cliff jumpers open their parachutes on the Moon?

( ) The parachutes would take longer to slow down the cliff jumpers on the Moon than on Earth.
( ) The parachutes would take less time to slow down the cliff jumpers on the Moon than on Earth.
( x ) The parachutes have no effect on the Moon.

No air so no value in a parachute either. Just extra weight that would have absolutely no effect on the speed or acceleration of the cliff jumpers (or any skydivers on the Moon).

FIGURE 10.7: Michael Phelps of the U.S. doing the butterfly stroke

https://www.sportphotogallery.com/content/images/cmsfiles/product/17884/17884-list.jpg

To finish this chapter, let's now turn to the other fluid we studied - water. In particular, I want to consider swimming on the Moon. We'll assume an enclosed pool area (with air) so the only difference will be gravity. What happens?

A swimmer jumps in a pool on Earth. Let's assume he floats. Now he jumps into a Moon pool. Is anything different? Same mass but his weight is less by a factor of 6.

QUIZ 10.29

What happens when a swimmer jumps into a pool on the Moon?

( ) The swimmer sinks deeper in the Moon pool.
( ) The swimmer sinks less in the Moon pool.
( x ) The swimmer floats just the same on the Moon as on Earth.

This was sort of a trick question. My first thought may have been the same as yours - since the swimmer's weight is less on the Moon, he or she won't sink as much. Not so. Let's see why.

To understand this, we need to remember why an object floating at rest in water does <u>not</u> sink. What is the force that opposes the weight and keeps an object from sinking? (Hint: see section 8.6.)

QUIZ 10.30

What force keeps an object in water from sinking?

( ) Weight
( ) Tension
( ) Normal Force
( x ) Buoyant Force
( ) Magnus Force

Hopefully you chose correctly.

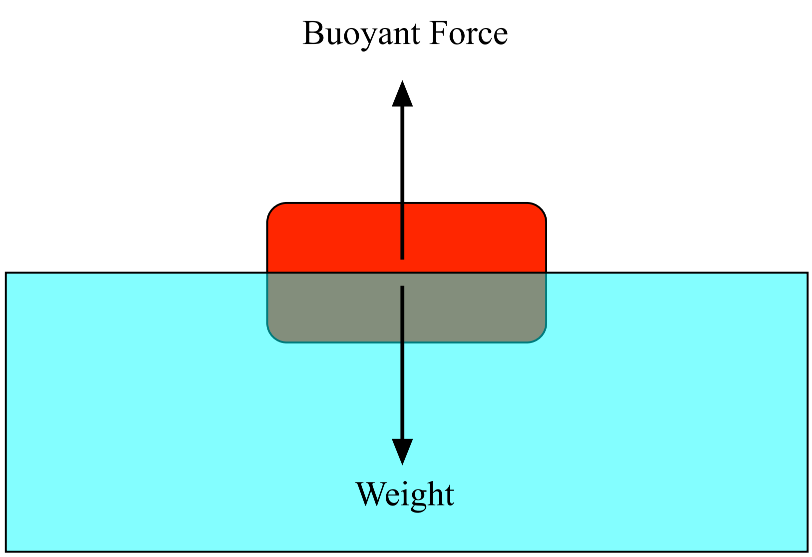



FIGURE 10.8: Free Body Diagram of a floating object

As illustrated above, the buoyant force must equal the weight of the object if it is to float. The magnitude of this force is given by Archimede's Principle: the buoyant force is equal to the weight of the water displaced. That's the key here. The object (the swimmer in our discussion) weighs 6 times less on the Moon. However, the water also weighs 6 times less. So the same amount of water is needed to hold up the swimmer. Basically these weights cancel so the swimmer (or any object) floats just as much or little on the Moon as on Earth.

Now to the swimming process itself. The swimmer pushes on the water. The water pushes back on the swimmer which makes the swimmer accelerate forward. (According to which of Newton's Laws?) But the water weighs 6 times less on the Moon than on Earth. Is that what matters?

QUIZ 10.31

When the swimmer applies a force and pushes on the water causing it to accelerate, what aspect of the water is important in determining its acceleration?

( ) The weight of the water
( x ) The mass of the water

Since F = ma, when the swimmer applies a force to the water, it is the *mass* not the weight that determines the acceleration. In addition, from Chapter 8 the drag force of the water depends on speed and cross-sectional area of the swimmer, and the density of water, none of which will be different on the Moon.

My conclusion: swimming on the Moon will be more or less the same as on Earth. Surprising isn't it? I think so. Of course, related activities such as the initial dive or jump into the pool at the start of a heat will be modified by the reduced gravity, but not the actual swimming motion. Can you think of any other sports that would *not* be affected by being held on the Moon?

Well, there are many other sports we discussed in this book (or didn't discuss at all) that did not make it into this chapter but would be affected by a change in venue to the Moon. Maybe you can think about some of the sports that were left out.

**Chapters 10 Homework**

For some of the questions and exercises below, we will imagine various sports and physics activities being carried out on the planet Jupiter. Jupiter is the most massive planet in the solar system. The gravitational force near the surface (which is rather ill-defined since there apparently is no solid surface on the planet - a challenge for Jovian sports!) is ~2.5 times the gravitational force on the surface of the Earth. The atmosphere is ~10 times thicker (depending on where you measure it) than on Earth (and the atmosphere is poisonous - but we'll deal with that somehow).

Questions

1. A 20 lb bowling ball is carried to Jupiter.
   a. How will the mass of the ball on Jupiter compare to the mass on Earth?

(A) The mass will be the same.
(B) The mass on Jupiter will be greater.
(C) The mass on Jupiter will be less.

Answer: (A)

b. How will the weight of the ball on Jupiter compare to the weight on Earth?

(A) The weight will be the same.
(B) The weight on Jupiter will be greater.
(C) The weight on Jupiter will be less.

Answer: (B)

2. Where should a basketball rim be placed on a Jovian court to make the competition comparable to Earth?

(A) The rim should be placed at the same height as on Earth (10 feet).
(B) The rim should be placed at a lower height than on Earth.
(C) The rim should be placed at a greater height than on Earth.

Answer: (B)

3. On the Moon we expect the trajectory of a shot put to be a perfect parabola. What about on Jupiter?

(A) The trajectory should also be a perfect parabola on Jupiter.
(B) The trajectory should not be a perfect parabola on Jupiter.

<u>Answer</u>: (B)

4. On Jupiter what would cause the trajectory of a shot put not to be perfect parabola?

(A) The greater gravitational force on Jupiter vs. the Earth.
(B) The Jovian atmosphere.
(C) The temperature of the planet.

<u>Answer</u>: (B)

5. Compare the range and height of a shot put on Earth and Jupiter.

(A) The range and height should both be greater on Jupiter than on Earth.
(B) The range and height should both be less on Jupiter than on Earth.
(C) The range and height should both be the same on Jupiter as on Earth.
(D) The range should be the same on Jupiter as on Earth but the height should be less.
(E) The height should be the same on Jupiter as on Earth but the range should be less.

<u>Answer</u>: (B)

6. A diver steps off a 3 meter diving board on Earth. Compare what happens on Jupiter.

(A) The diver will hit the water with the same speed on Jupiter as on the Earth.
(B) The diver will hit the water with a greater speed on Jupiter than on the Earth.
(C) The diver will hit the water with a reduced speed on Jupiter than on the Earth.

<u>Answer</u>: (B)

7. The hammer and feather drop demo is repeated on Jupiter. What happens?

(A) The hammer and feather hit the surface at the same time.

(B) The hammer hits the surface before the feather.
(C) The feather hits the surface before the hammer.

Answer: (B)

8. In a Jovian pole vault competition, assuming that the vaulter can achieve the same speed on Jupiter as on Earth (not a very good assumption) during the approach, compare the elastic energy stored in the pole before the vaulter's take-off.

(A) The elastic energy stored in the pole will be the same on Jupiter as on Earth.
(B) The elastic energy stored in the pole on Jupiter will be greater than on Earth.
(C) The elastic energy stored in the pole on Jupiter will be less than on Earth.

Answer: (A)

9. In a Jovian pole vault competition, assuming that the vaulter can achieve the same speed on Jupiter as on Earth (not a very good assumption) during the approach, compare the maximum height of the pole vault attempt on Jupiter to Earth.

(A) The pole vault height will be the same on Jupiter as on Earth.
(B) The pole vault height on Jupiter will be greater than on Earth.
(C) The pole vault height on Jupiter will be less than on Earth.

Answer: (C)

10. a. In the Jupiter's Strongest Man competition, is the Atlas Stones event as carried out on Earth more or less challenging on Jupiter?

(A) more challenging
(B) less challenging
(C) the same

Answer: (A)

b. Explain.

11. On the Moon, a pitcher could not throw a curve ball. What about on Jupiter?

(A) A Jovian pitcher can throw a curve ball.
(B) A Jovian pitcher cannot throw a curve ball.

Answer: (A)

12. A block is hanging from a spring on Earth, which causes the spring to be stretched by 0.1 meter. If this block and spring arrangement were set up on Jupiter instead, what would be different?

(A) There would be no change in the stretch of the spring.
(B) The stretch of the spring would increase.
(C) The stretch of the spring would decrease.

Answer: (B)

13. You try sliding on the "surface" of Jupiter. Compare the frictional force between shoe and ground to that on Earth?

(A) The frictional force will be greater on Jupiter.
(B) The frictional force will be less on Jupiter.
(C) The frictional force will be the same on Jupiter.

Answer: (A)

14. Shaquille O'Neal hangs on a basketball rim on the Moon. How much does the rim bend compared with on Earth.

(A) The rim bends the same amount on the Moon as on Earth.
(B) The rim bends less on the Moon as on Earth.
(C) The rim bends more on the Moon as on Earth.

Answer: (B)

15. Shaquille O'Neal hangs on a basketball rim on Jupiter. How much does the rim bend compared with on Earth.

(A) The rim bends the same amount on Jupiter as on Earth.
(B) The rim bends less on the Jupiter as on Earth.
(C) The rim bends more on the Jupiter as on Earth.

Answer: (C)

16. You are riding a bicycle on the Earth. You hit the brakes and come to a stop in 3 meters. Traveling at the same speed on the Moon, you apply your brakes. Compare the braking distances.

(A) On the Moon, the bike will come to rest in 3 meters.
(B) On the Moon, the bike will come to rest in less than 3 meters.
(C) On the Moon, the bike will come to rest in more than 3 meters.

Answer: (C)

17. A skydiver on the Moon originally jumping straight down adopts a spread-eagle configuration. What happens?

(A) The skydiver slows down.
(B) The skydiver speeds up.
(C) The skydiver's speed does not change.

Answer: (C)

18. A skydiver on Jupiter originally jumping straight down adopts a spread-eagle configuration. What happens?

(A) The skydiver slows down.
(B) The skydiver speeds up.
(C) The skydiver's speed does not change.

Answer: (A)

19. Golf on the Moon (outdoors). Which golf ball travels further?

(A) A smooth golf ball.
(B) A dimpled golf ball.
(C) They should travel the same distance.

Answer: (C)

20. Two skydivers jump out of a plane on the Moon. Skydiver A has a parachute that is twice the size of the parachute of skydiver B. What happens?

(A) Skydiver A hits the Moon's surface before skydiver B.
(B) Skydiver B hits the Moon's surface before skydiver A.

(C) They hit the surface at the same time.

Answer: (C)

21. Two skydivers jump out of a plane on Jupiter. Skydiver A has a parachute that is twice the size of the parachute of skydiver B. What happens?

(A) Skydiver A hits Jupiter's surface before skydiver B.
(B) Skydiver B hits Jupiter's surface before skydiver A.
(C) They hit the surface at the same time.

Answer: (B)

22. Should diving platforms be raised on the Moon or not? Explain your reasoning.

23. How would you modify the Alas Stone event of the Moon's Strongest Man competition to make it as equally challenging as the one on Earth?

24. How would you modify the Alas Stone event of Jupiter's Strongest Man competition to make it as equally challenging as the one on Earth?

25. Cycling on the Moon - indoor track. What will be different from Earth?

26. Cycling on the Moon - outdoor track. What will be different from Earth?

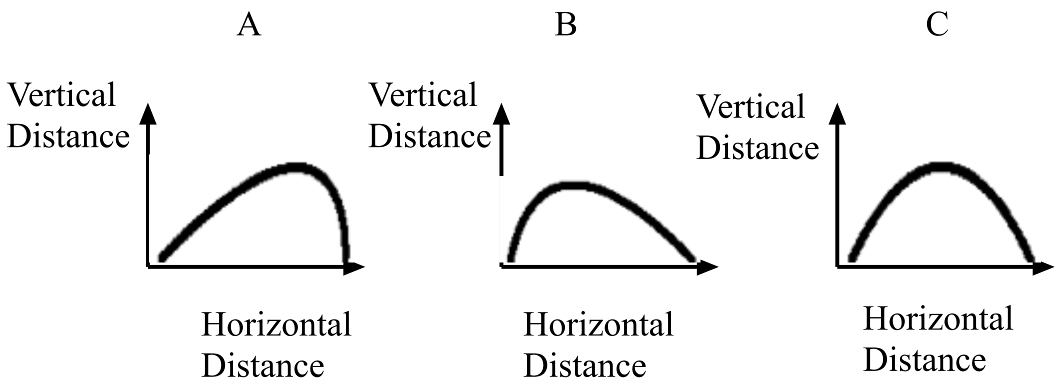
27. Explain what would be different about throwing a Frisbee on the Moon.

Answer: It wouldn't "coast".

28. You get into a glider launched off a cliff on the Moon. What happens?

(A) You glide a greater distance on the Moon than on Earth.
(B) You glide a lesser distance on the Moon than on Earth
(C) You don't glide on the Moon, but drop almost straight down.

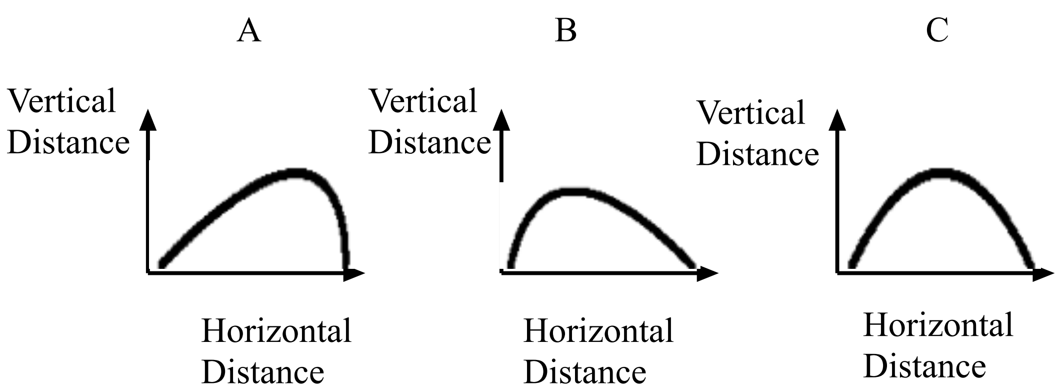
Answer: (C)




29. A shot is thrown on the Moon. Which plot best depicts the trajectory of the shot?

______________

Answer: (C)




30. A shot is thrown on Jupiter. Which plot best depicts the trajectory of the shot?

_____________

Answer: (A)

31. Would a helium-filled balloon float above the Moon's surface? Explain.

32. Discuss how you would modify the game of baseball on the Moon to keep the size of the stadium and playing field about the same as on Earth.

## Exercises

1. A 17 kilogram curling stone is carried to Jupiter. What is the mass of the curling stone on Jupiter?

____________ kilograms

Answer: 17 kilograms

2. A 17 kilogram curling stone is carried to Jupiter. What is the weight of the curling stone on Jupiter?

____________ Newtons

Answer: 425 Newtons

3. A 7.26 kilogram men's shot is carried to the Moon.

a. What is the mass of the shot on the Moon?

____________ kilograms

b. What is the weight of the shot on the Moon?

____________ Newtons

Answer:
a. 7.26 kilograms
b. 12.1 Newtons

4. Shaquille O'Neal's playing weight was listed at 325 pounds.

a. What would be his weight on the Moon?

____________ pounds

Answer: 54.2 pounds

b. What would be his weight on Jupiter?

____________ pounds

Answer: 812.5 pounds

5. Instead of a height of ~3 meters on Earth, where should a basketball rim be placed on a Jovian court to make the competition comparable to Earth? (Hint: refer to the discussion about Jordan's dunks on the Moon in section 10.1.)

(A) 1 meter
(B) 2 meters.
(C) 2.5 meters
(D) 3.5 meters.
(E) 4 meters

Answer: (C)

6. An 80 kilogram runner runs on Earth with a speed of 5 meters per second.
a. Find the kinetic energy of the runner.

____________ Joules

Answer: 1000 Joules

b. Assuming she achieves the same speed on the Moon, find her kinetic energy on the Moon.

____________ Joules

Answer: 1000 Joules

7. To make the Atlas Stones event in the Jupiter's Strongest Man competition comparable (in terms of the work done) to Earth's, how high should the pedestals for the stones be made (vs. ~2 meters on Earth)?

(A) 0.8 meter
(B) 1.2 meters
(C) 1.5 meters
(D) 5 meters

<u>Answer</u>: (A)

8. A 120 kilogram man stands on the surface of the Moon. What is the normal force exerted on the man by the Moon's surface?

____________ Newtons

<u>Answer</u>: 200 Newtons

9. A 120 kilogram man stands on the surface of Jupiter. What is the normal force exerted on the man by Jupiter's surface?

____________ Newtons

<u>Answer</u>: 3000 Newtons

10. On Earth a shot is thrown straight up into the air with an initial speed of 15 meters per second. It will take ~3 seconds before it hits the ground. On Jupiter, the same shot is throw up into the atmosphere with the same initial speed. How long will it take the shot to hit the ground?

(A) 1.2 seconds
(B) 1.9 seconds
(C) 3 seconds
(D) 4.7 seconds
(E) 7.5 seconds

<u>Answer</u>: (A)

11. The current record for the shotput on Earth is ~80 feet. What should we expect the Jovian shotput record to be?

(A) 16 feet
(B) 20 feet
(C) 32 feet
(D) 40 feet
(E) 60 feet

Answer: (C)

12. a. A shot is dropped from a cliff on the Earth. Ignoring air resistance (is this a good assumption?), what is the speed of the shot after 2 seconds?

____________ meters per second

b. A shot is dropped from a cliff on the Moon. Ignoring air resistance (is this a good assumption?), what is the speed of the shot after 2 seconds?

____________ meters per second

c. A shot is dropped from a cliff on Jupiter. Ignoring air resistance (is this a good assumption?), what is the speed of the shot after 2 seconds?

____________ meters per second

Answers: a. 20 meters per second
b. 3.33 meters per second
c. 53.3 meters per second

13. A skydiver with a weight of 2500 Newtons on Jupiter reaches his terminal speed above the Jovian surface. What is the magnitude of the drag force?

____________Newtons

Answer: 2500 Newtons

14. A skydiver with a mass of 50 kilograms on Jupiter falls from rest for 1 second towards the Jovian surface. Ignoring atmospheric resistance, find the kinetic energy of the skydiver at this time.

____________ Joules

Answer: 15,625 Joules

15. A skydiver with a weight of 2000 Newtons on Jupiter falls from rest for 3 seconds towards the Jovian surface. Ignoring atmospheric resistance, find the kinetic energy of the skydiver at this time.

____________ Joules

Answer: 225,000 Joules

16. A skydiver with a mass of 50 kilograms on Jupiter falls from rest through a distance of 50 meters towards the Jovian surface. Ignoring atmospheric resistance, find the kinetic energy of the skydiver at this position. (Hint: use Conservation of Energy.)

____________ Joules

Answer: 62,500 Joules

17. A strong man on the Earth raises a 100 kilogram Atlas stone a distance of 2 meters. Assume that he expends ~1000 calories to raise the stone. Approximately how many calories would he expend on the Moon for the same event?

____________ calories

Answer: 167 calories

18. A strong man on the Earth raises a 100 kilogram Atlas stone a distance of 2 meters. Assume that he expends ~1000 calories to raise the stone. Approximately how many calories would he expend on Jupiter for the same event?

____________ calories

Answer: 2500 calories

19. A swimmer with a weight of 100 Newtons on the Moon is floating in a swimming pool. What is the magnitude of the buoyant force on the swimmer?

____________ Newtons

Answer: 100 Newtons

20. A swimmer with a mass of 70 kilograms on the Moon is floating in a swimming pool. What is the magnitude of the buoyant force on the swimmer?

____________ Newtons

Answer: 117 Newtons

21. The current record for the pole vault on Earth is 6 meters What should we expect the Jovian pole vault record to be?

(A) 2 meters
(B) 3 meters
(C) 4 meters
(D) 5 meters
(E) 6 meters

Answer: (B)

22. The highest peak on the bright side of the Moon (the side facing Earth) is Mons Huygens with an elevation of 4.7 kilometers. How much work would it take to carry a 4 kilogram shot to the top of the mountain from "sea level"?

____________ Joules

Answer: 31,333 Joules

23. The highest point on the Moon is on the dark side of the Moon (the side facing away from the Earth) with an elevation of 11.2 kilometers. What is the power needed to climb to the top of this peak from "sea level" assuming a mass of 80 kilograms and that the trip takes 8 hours?

____________Watts

Answer: 69 Watts

24. You push against a football tackling sled on Earth with a force of 700 Newtons. The sled is *just about to move*. On Jupiter, with how much force would you need to push the sled to just get it to move?

____________ Newtons

Answer: 1750 Newtons

25. On Earth, a diver stepping off a 3 meter diving board would enter the water with a speed of ~14 meters per second. With what speed would the diver enter the water in a Jovian pool?

____________ meters per second

Answer: 22 meters per second

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## Activities

- pick a sport as a team and discus various physics aspects of it
- build a gravity board and measure centers of gravity of students
- video and analyze billiard collisions for conservation of momentum and of kinetic energy
- video and analyze air hockey collisions for conservation of momentum and of kinetic energy/put velcro on pucks and study inelastic collisions
- time students running on a track-vary distances; calculate average speeds
- video students running on a track
- time students swimming laps; vary distances; calculate average speeds
- video jumping off diving board-analyze to get g
- video balls and ping pong balls-examples of 2D motion; get g; constant speed in x direction?
- drag sneakers and shoes and get coefficient of friction-different coatings on bottom
- bounce balls and measure coefficients of restitution-compare to book values; vs. pressure and temperature of balls
- measure reaction times in various ways
- have students lead discussions comparing class results to elite athletes
- analyze some circular motion like skating-get revolution time
- plot various world records vs. time and discuss-technology vs. technique vs. nutrition, etc.
- look for videos on web of curving balls
- force plate measurements-jumping; jumping on padding; pushing
- video 2D motion-angles of takeoff vs. range
- force plate-impulse/time
- measurements with bikes
- egg drop on foam, etc.
- look for center of percussion, etc. for rackets and bats
- do measurements on ice-friction-push off, video sliding
- find examples of friction in sports
- find examples of center of mass in sports
- find hang time videos
- find examples of uniform circular motion
- find examples of banked tracks
- find examples of angular acceleration
- find examples of changes in moment of inertia
- find examples of swing weight
- more examples of reaction times in sports
- find more reaction time tests
- different kinds of reaction times
- drop balls on carbon paper
- factors affecting reaction times

- examples of bouncing or colliding, spinning balls
- research physiological limits to reaction times
- analyze videos for angles of launch of various projectiles
- check areas and speeds of various projectiles
- look up the effects of wind on sports projectiles
- test or research limits of roughening a ball to improve its travel distance
- research other examples of spins-tennis (2nd serve), football

## Class Stuff

Equipment
stopwatches (~6)
video camera with tripod
force plate + hand held data logger
balls (golf, superball, basketball, football, soccer ball, baseball, softball, hockey puck)
pump for basketball
pressure gauge (or pump reading)
long tape measure (at least 25 meters)
pool playing apparatus (for videotaping)
projectile launcher (probably)
rulers for reaction time measurements
gravity board apparatus
compression springs
clipboards

Questions/Issues related to class measurements.

- For a normal run or swim, how much of the course is run/swum at constant speed?
- Does this depend of the length attempted?
- How do average results compare to elite athletes in running and swimming?
- Does the acceleration of a diver come close to g?
- Does this depend on whether the arms, etc. are tucked in or not?
- If a swimmer runs with a object dragging behind, how much difference does this make?
- Throwing different balls around, can we detect the effects of air resistance?
- How do average throwing speeds and maximum distances (ranges) compare with elite athletes?
- How do average throwing speeds and maximum distances (ranges) compare for different types of balls?
- Can we see the effect of angle on the maximum range of some balls?
- How does throwing a football or baseball with and without spin compare?
- Force plate-compare maximum forces for pushing and jumping.
- Force plate-look at jumping onto foam or for different types of shoes.
- Weights-maximum weights vs. elite athletes.
- Weights-work done and power vs. different weights.
- How much of the lift is at a constant speed vs. acceleration?
- How do measured COR's compare to standard values?
- COR vs. pressure in a basketball or vs. temp. for different balls.

- Determine centers of gravity vs. height. Any correlation?
- CORs for same balls, different surfaces.
- CORs for dropping vs. firing balls?
- Billiards-is KE conserved?
- Billiards-is momentum conserved?
- Billiards-can we detect the effects of friction?
- Impulse: effect of foam and other surfaces on jumping or dropping weights; bending knees vs. straight legs; get padding?