Major League Physics

Using Baseball to Teach Mechanics

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MAJOR LEAGUE PHYSICS

The Game Plan

1. Baseball on Mars
2. Properties of a Baseball Bat
3. Homers Using the Bulls Eye Apparatus
4. Ball-Bat Collisions
5. Aluminum Bats
6. Alan Nathan’s Talk
7. Coefficient of Restitution
8. PitchFX Primer
9. Curve Balls

MAJOR LEAGUE PHYSICS

Raffle!

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Baseball on Mars

MAJOR LEAGUE PHYSICS

Baseball on Mars

Atwood's Machine

$$F_{net} = ma$$

$$mg - \frac{mg}{2} = (m + \frac{m}{2})a$$

$$\frac{mg}{2} = \frac{3}{2}ma$$

$$a = \frac{g}{3}$$

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Baseball on Mars

Build the "Baseball on Mars" Atwood's Machine!

MAJOR LEAGUE PHYSICS

Baseball on Mars

- How would you have to modify the playing field so that the game on Mars is similar to a game played on Earth?

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Raffle!

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Properties of a Baseball Bat

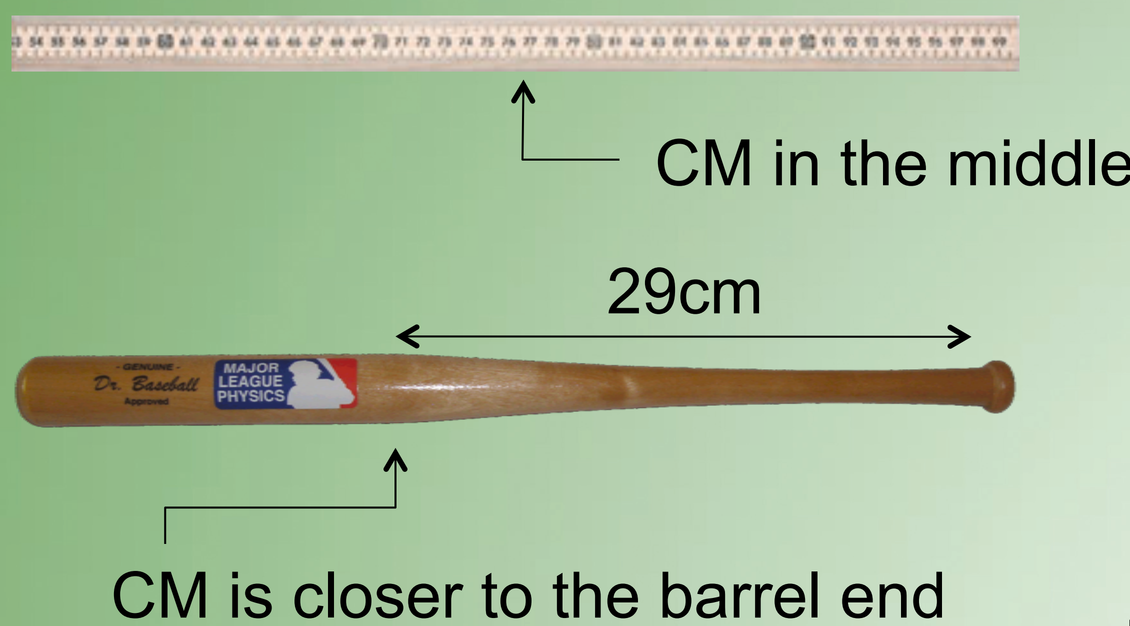
The center of mass (CM)

CM in the middle

Where is the CM of a real bat?

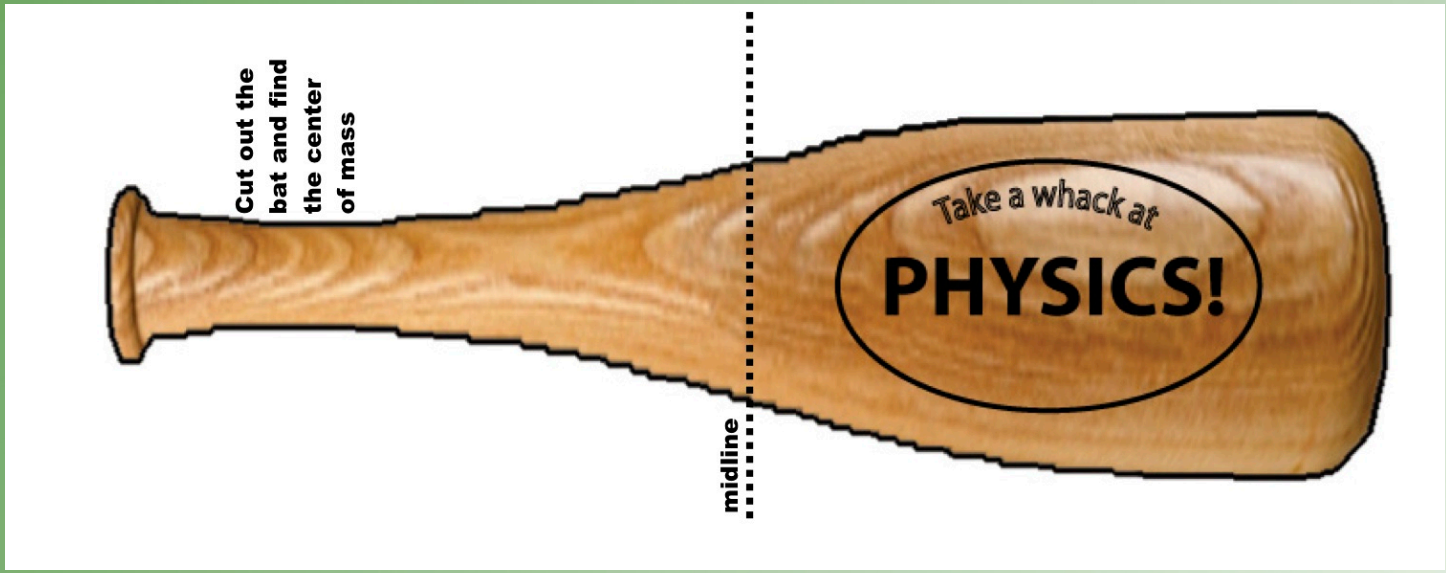
Properties of a Baseball Bat

The center of mass (CM)



Properties of a Baseball Bat

The center of mass (CM)



Cardstock bats

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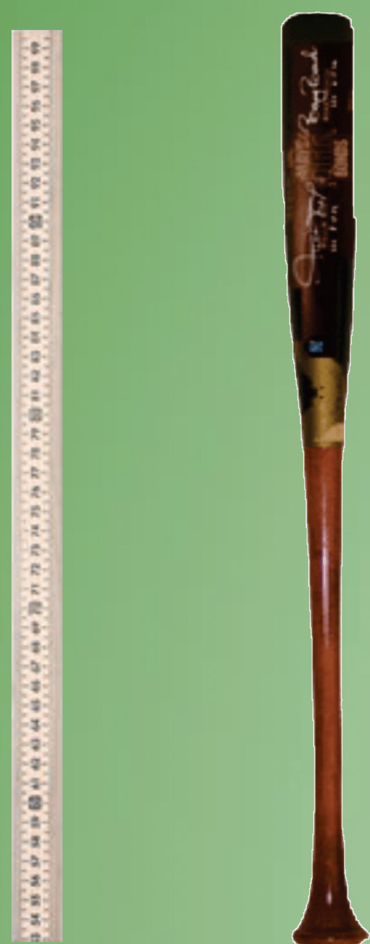
Properties of a Baseball Bat

The rotational inertia (MOI)



Rotational inertia is a measure of how hard an object is to rotate.

Which is it easier to balance on your hand, the bat or the meter stick?

Properties of a Baseball Bat

The rotational inertia (MOI)

Rotational inertia is a measure of how hard an object is to rotate.

Which is it easier to balance on your hand, barrel up or barrel down?

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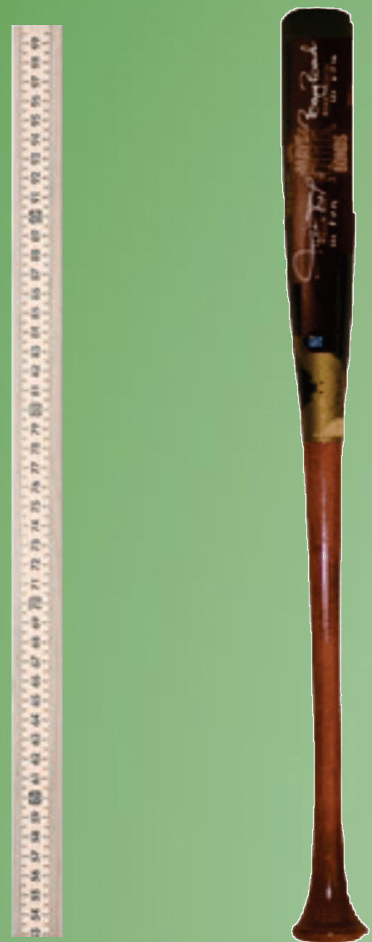
Properties of a Baseball Bat

The rotational inertia (MOI)



The bat has a larger rotational inertia about the handle than the meter stick.

Properties of a Baseball Bat

The rotational inertia (MOI) calculation

For a physical pendulum $T = 2\pi\sqrt{\frac{I}{mgr_{cm}}}$

So, $I = mgr_{cm}\frac{T^2}{4\pi^2}$ given m = 144g

Use a stopwatch to find the period and calculate the rotational inertia.

Did you get I = 0.013kg·m^2 ?

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Properties of a Baseball Bat

The center of oscillation (CO)

Physical
Pendulum

Simple
Pendulum

The CO is equal to the length of a simple pendulum with the same period as the bat.

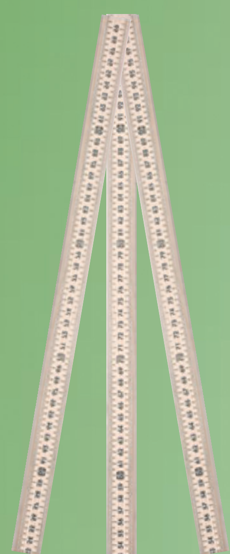
Did you get about 30cm?

MAJOR LEAGUE PHYSICS

Properties of a Baseball Bat

The center of oscillation (CO)

For the meter stick, the CO is 2/3 of the length.



For the bat, the CO is more than 2/3 of the length.

Properties of a Baseball Bat

Check your answer!

Physical
Pendulum

$$T = 2\pi\sqrt{\frac{I}{mgr_{cm}}}$$

Simple
Pendulum

$$T = 2\pi\sqrt{\frac{r_{co}}{g}}$$

$$\sqrt{\frac{r_{co}}{g}} = \sqrt{\frac{I}{mgr_{cm}}} \Rightarrow \frac{r_{co}}{g} = \frac{I}{mgr_{cm}} \Rightarrow I = mr_{co}r_{cm}$$

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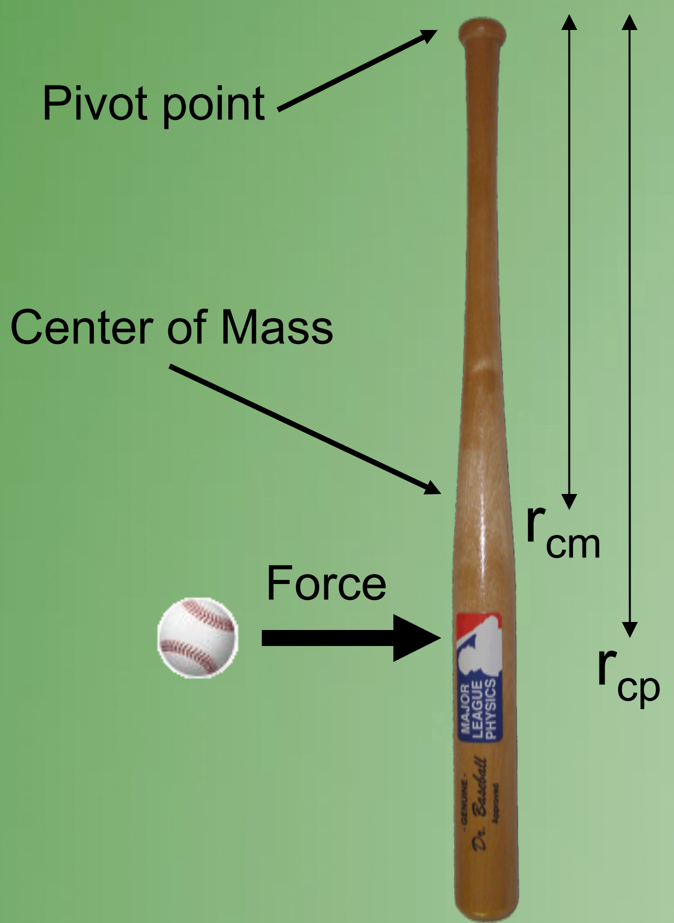
Properties of a Baseball Bat

The center of percussion (CP)

The spot were an applied force causes pure rotation about the end of the bat



Second Law for Rotation

$$\sum \tau = I\alpha$$

$$r_{cp}F = I\alpha$$

Pure Rotation

$$r_{cp}F = I\frac{a}{r_{cm}}$$

Second Law

$$r_{cp}ma = I\frac{a}{r_{cm}}$$

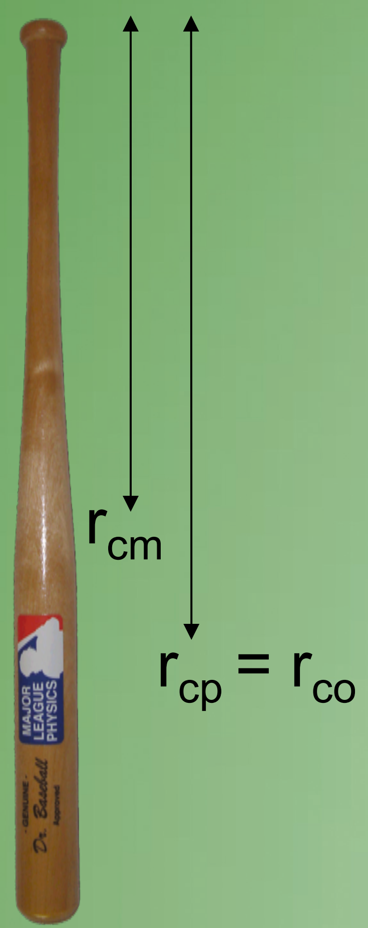
Center of Percussion

$$r_{cp} = \frac{I}{mr_{cm}}$$

but… $$r_{cp} = \frac{mr_{co}r_{cm}}{mr_{cm}} = r_{co}$$

Properties of a Baseball Bat

What have we learned?



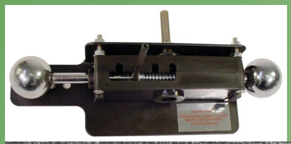
- The CM is further from the handle than the barrel end.
- The MOI can be found by timing the free oscillations of the bat.
- The CO can be found by finding the length of a simple pendulum with the same period as the bat.
- The CP is equal to the CO.
- The CP and CO are related to the MOI and CM.

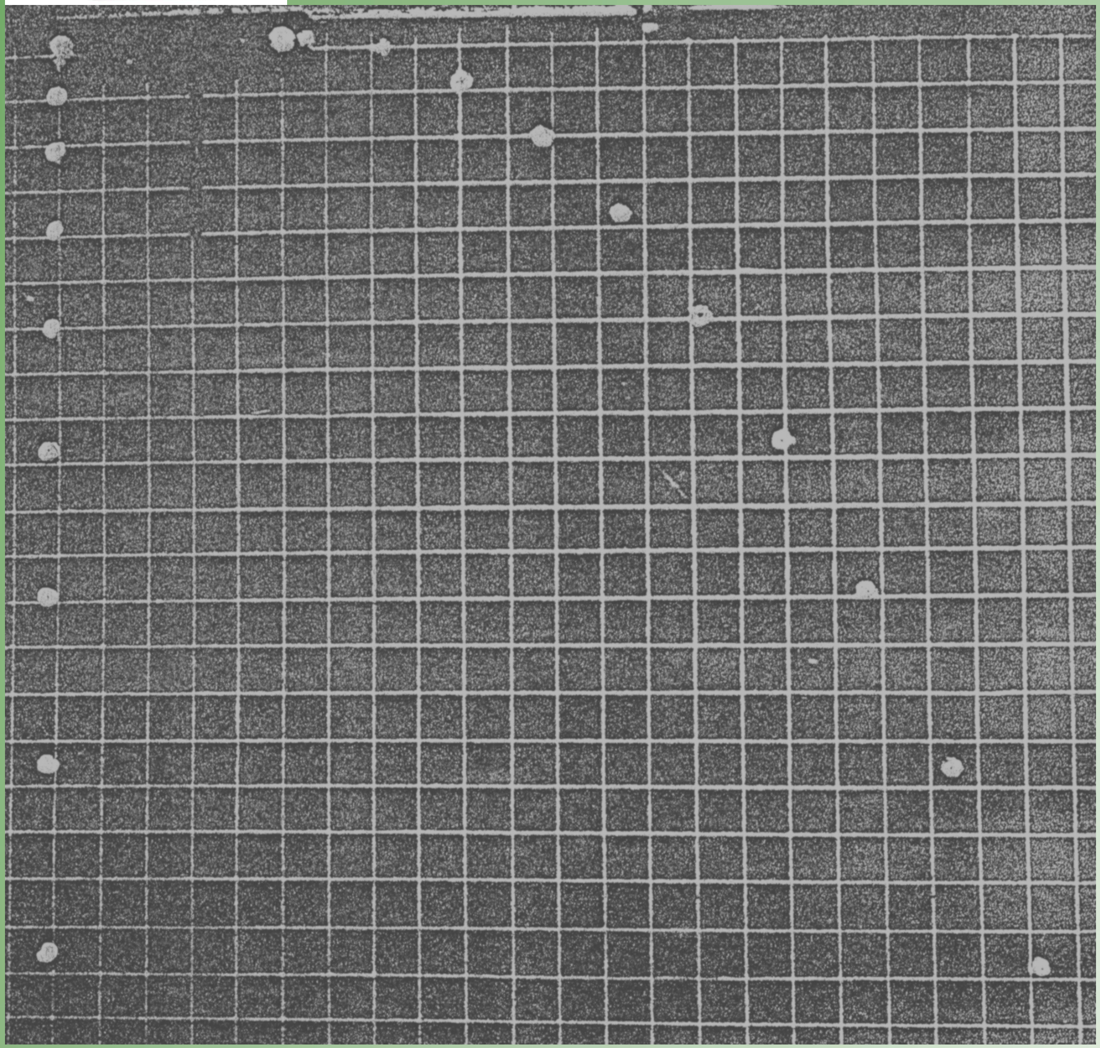
$$I = m r_{cp} r_{cm}$$

Raffle!

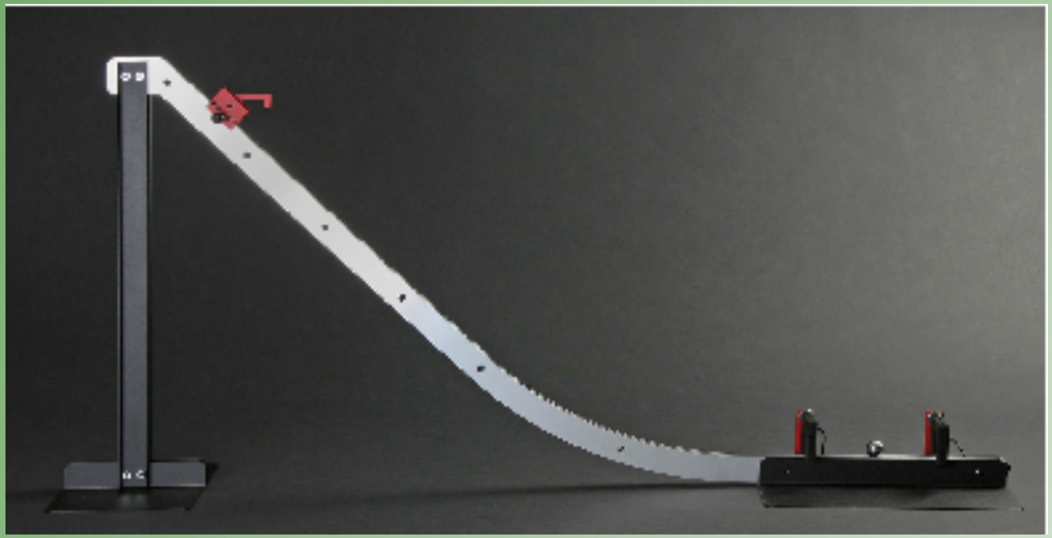
MAJOR LEAGUE PHYSICS

Homers and the Bull's Eye Apparatus





Homers and the Bull's Eye Apparatus



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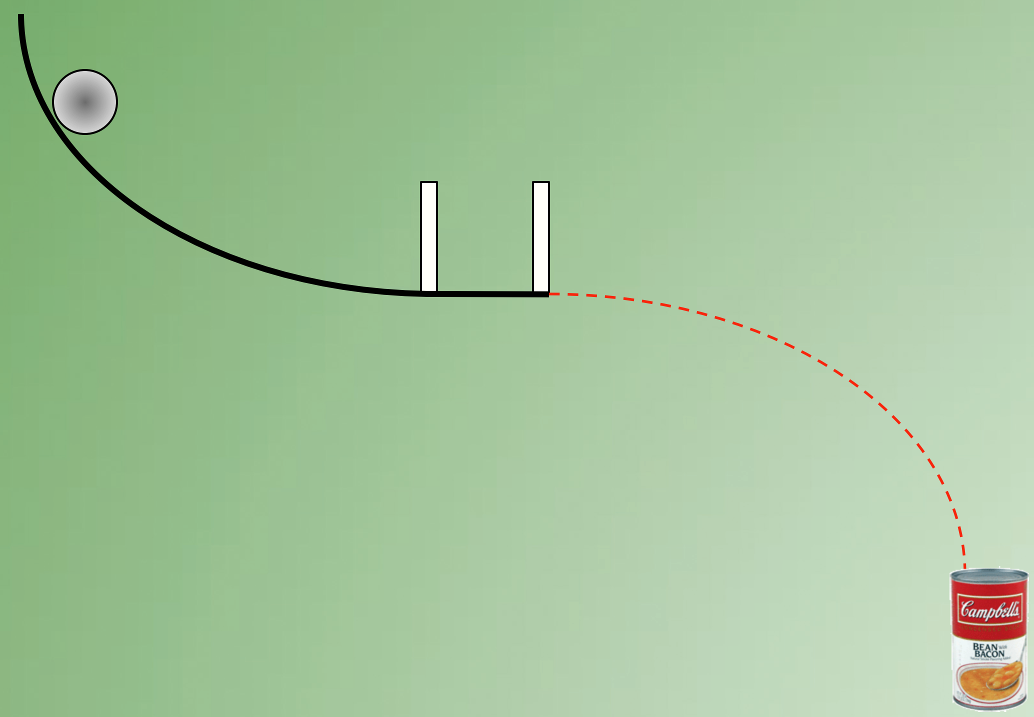
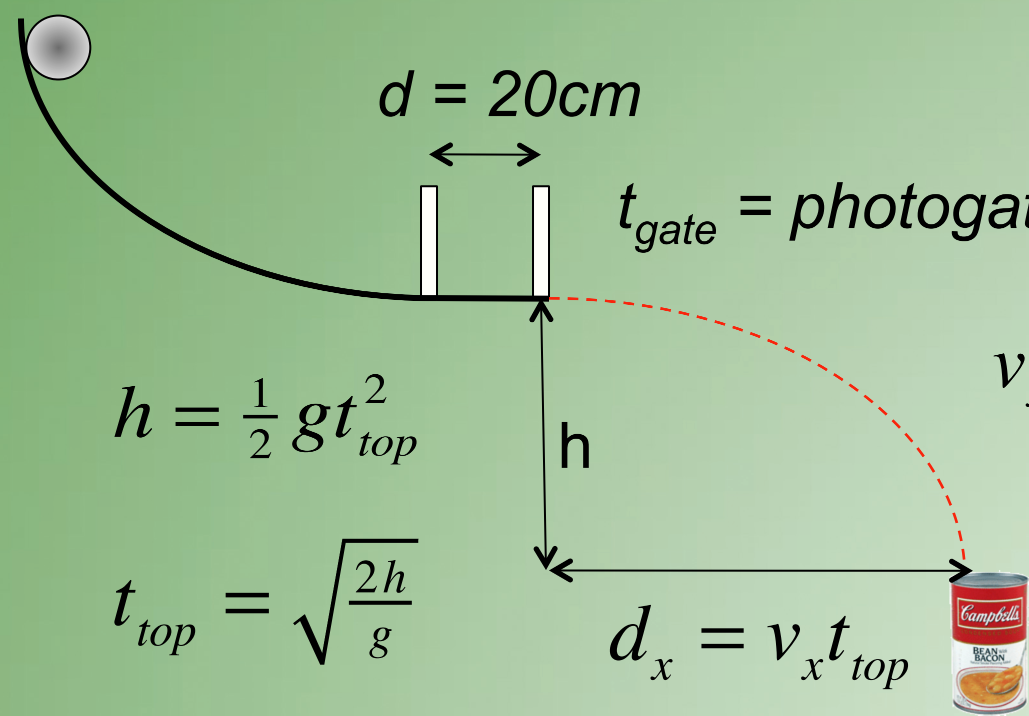
Homers and the Bull's Eye Apparatus



MAJOR LEAGUE PHYSICS

Homers and the Bull's Eye Apparatus



t_{gate} = *photogate time*

$$v_x = \frac{d}{t_{gate}}$$

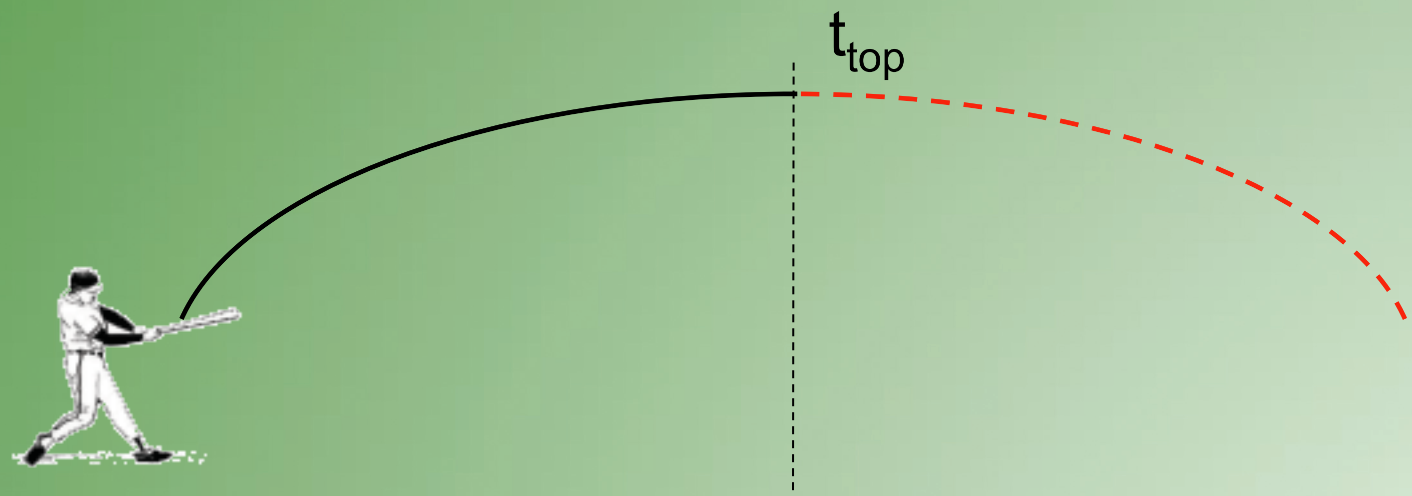
$$h = \tfrac{1}{2} g t_{top}^2$$

$$t_{top} = \sqrt{\frac{2h}{g}}$$

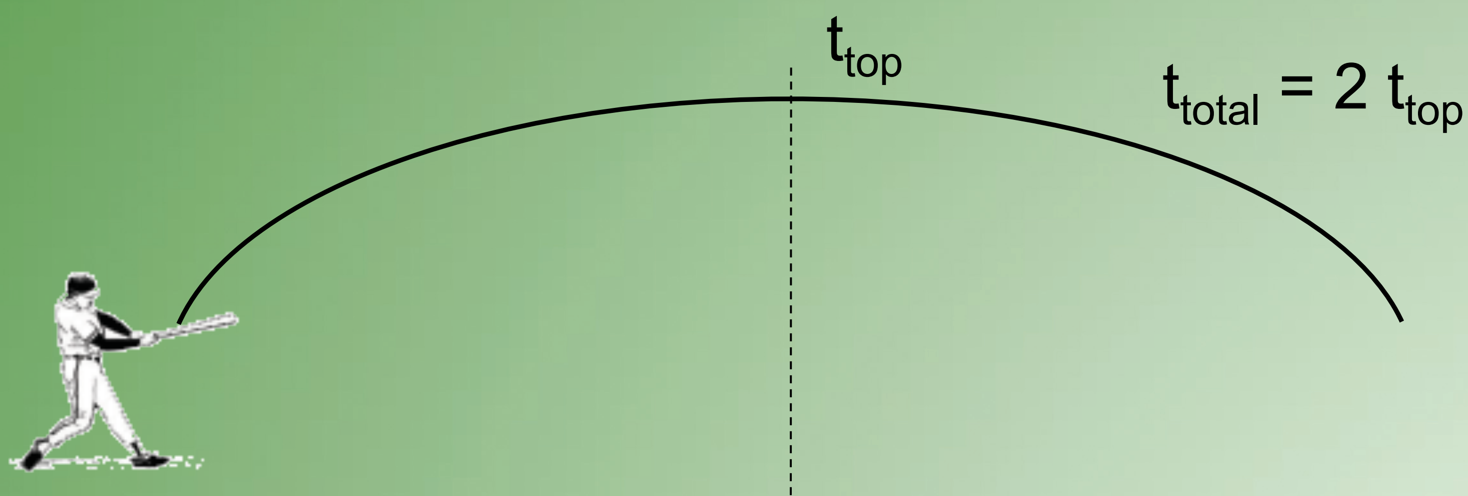
$$d_x = v_x t_{top}$$

MAJOR LEAGUE PHYSICS

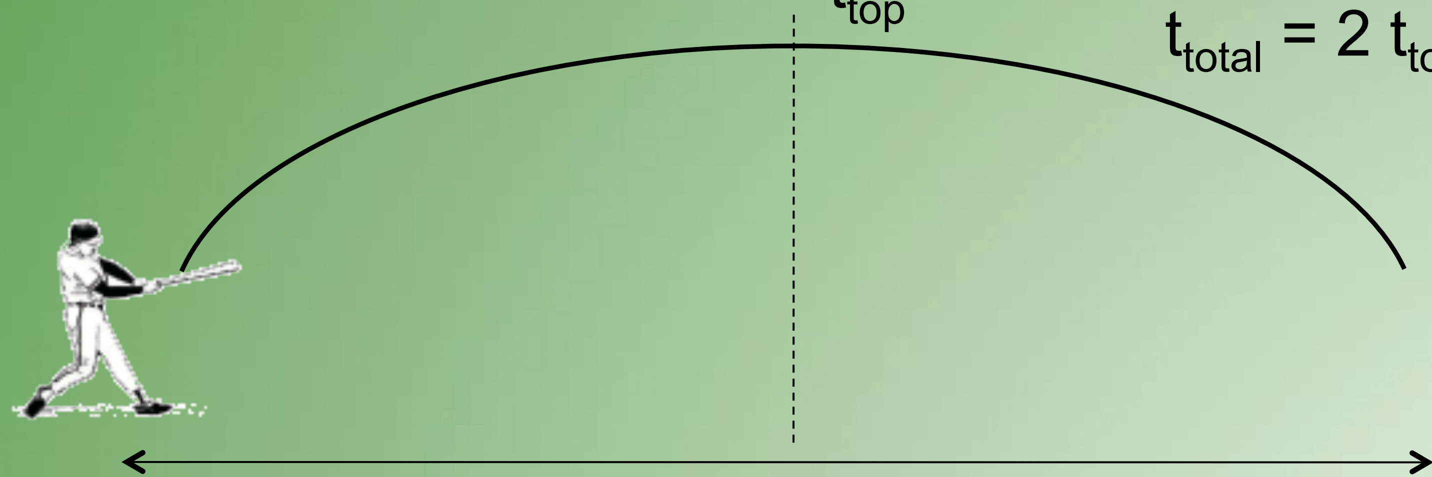
Homers and the Bull's Eye Apparatus



Homers and the Bull's Eye Apparatus



Homers and the Bull's Eye Apparatus



t_{top}

$t_{total} = 2\ t_{top}$

$d_{homer} = v_x\ (\ 2\ t_{top}\ )$

MAJOR LEAGUE PHYSICS

Raffle!

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Ball-Bat Collisions

High Speed Camera during the 2012 Playoffs

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Ball-Bat Collisions

Conservation of Momentum

Ball-Bat Collisions

Conservation of Momentum

Ball-Bat Collisions

To understand the images produced by the camera we need to investigate two key ideas:

- Center of Percussion (CP)
- Vibrational Nodes (VN)

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Ball-Bat Collisions

Center of Percussion (CP)

We locate the CP by finding where we can hit the stick so that there is no jerk at the top. In other words, the bat goes into pure rotation.

For the simple stick the CP is 2/3 of the way down the bat.

This is where you want to hit the ball so you don't get thrown around by the motion of the bat handle.

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Ball-Bat Collisions

Vibrational Nodes (VN)

You can demonstrate vibrational nodes with a flexible stick.

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Ball-Bat Collisions

If you wrap a paper megaphone around the top of the stick you can hear the vibrations.

The place where the sound is minimum is the VN. For the simple stick, the node is ¾ of the way down the bat.

At the node, little energy will go into bat vibrations, leaving more energy in the ball.

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Ball-Bat Collisions

The CP and the VN are in different spots for a simple stick.

If we could redistribute the mass of the stick, perhaps we could get them to overlap.

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Ball-Bat Collisions

A bat is shaped like it is because the CP and the VN are in the same spot –

“The Sweet Spot.”

Ball-Bat Collisions

The New York Times

The Mets' Bat Whisperer

Uli Seit for The New York Times

Some people might consider the Mets slugger Carlos Beltran an eccentric: when he receives a new box of bats he likes to listen to them. "It's part of me," he said.

By DAVID WALDSTEIN
Published: June 11, 2011

Ball-Bat Collisions

Ball-Bat Collisions

Using this rubber bat, you can actually see the “sweet spot!”

Raffle!

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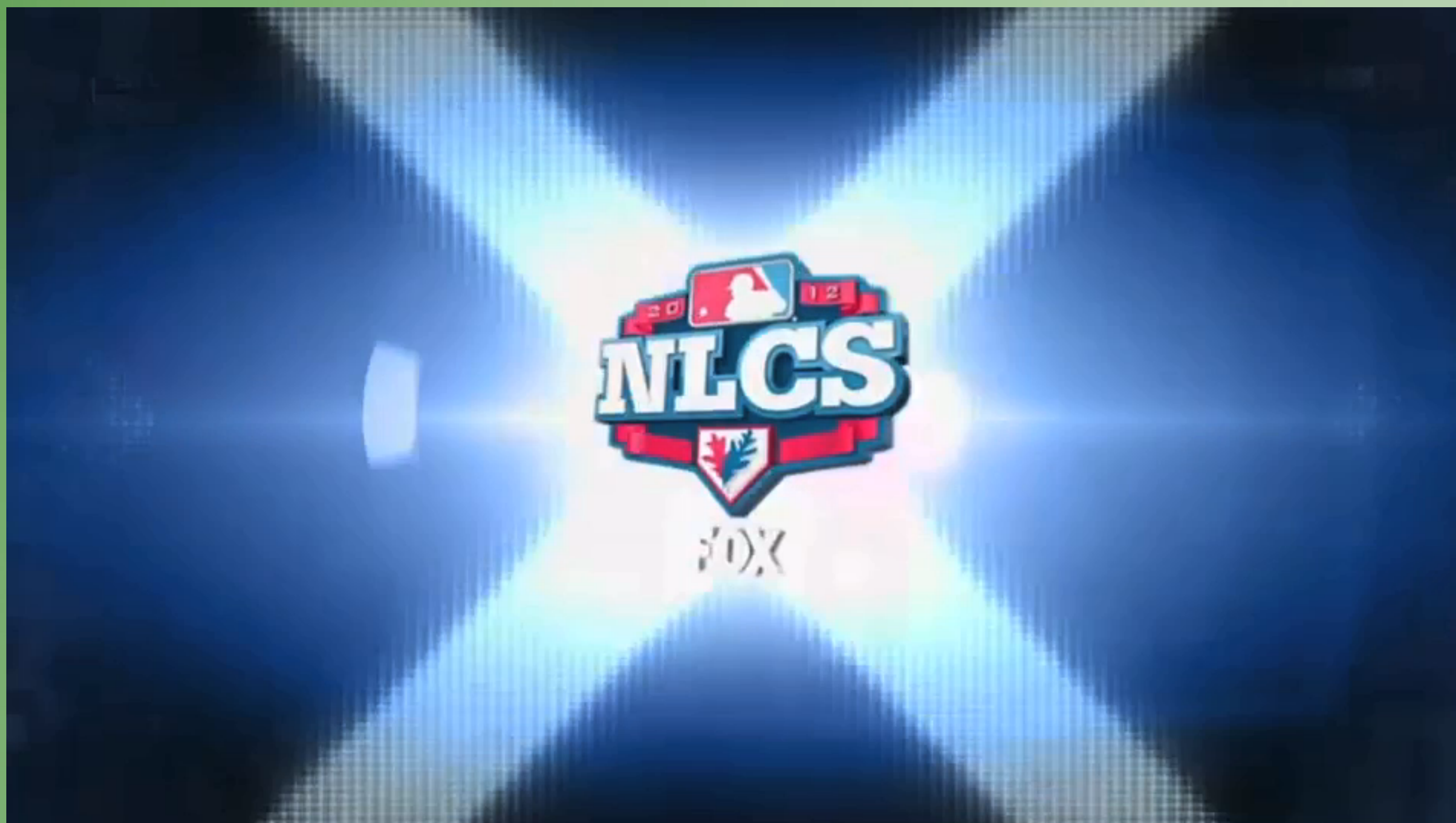
Ball-Bat Collisions

Back to the images from the camera…

Ball-Bat Collisions

Inside the Sweet Spot



Ball-Bat Collisions

Outside the Sweet Spot

Ball-Bat Collisions

On the Sweet Spot!

Ball-Bat Collisions

On the Sweet Spot!

Ball-Bat Collisions

Breaking Bat?

The bat breaks because the amplitude of the vibrations exceeds the elastic limit of the wood fibers in the bat. This always occurs at where the bat is thin – at the handle – regardless of where the ball hits the bat.

MAJOR LEAGUE PHYSICS

Ball-Bat Collisions

Broken Bat Outside the Sweet Spot

Ball-Bat Collisions

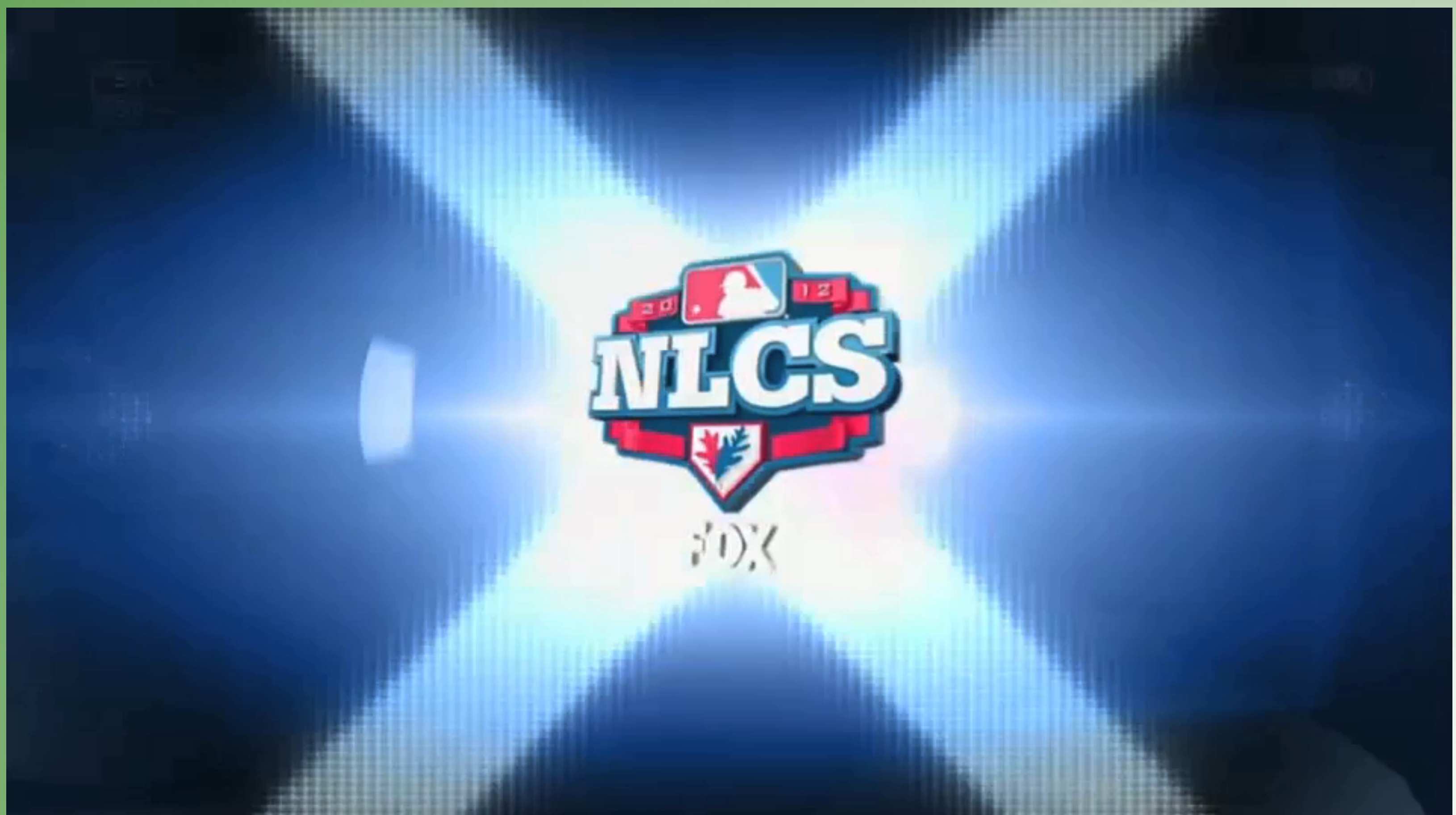
Broken Bat Inside the Sweet Spot

Ball-Bat Collisions

Why does the Cardinal's shortstop move the wrong way at this critical moment in Game 7 of the 2012 NLCS?

Ball-Bat Collisions

The high speed camera reveals a truly remarkable event.



Ball-Bat Collisions

The high speed camera reveals a truly remarkable event.

Ball-Bat Collisions

What have we learned?

- A baseball bat is shaped in such a way to have a "sweet spot."
- The sweet spot is due to the fact that the CP and the VN coincide.
- The vibration of the bat takes energy away from the ball. So, well hit balls are struck at the sweet spot.
- The bat breaks when large amplitude vibrations reach the thin part of the handle.
- All of this is verified in actual games with high speed video.

Raffle!

MAJOR LEAGUE PHYSICS

Aluminum Bats

Bats have evolved over time.

Aluminum Bats

The bat has evolved from almost a simple stick to a precisely engineered device

Simple Stick

Modern Wooden Bat

Aluminum Bat

What does physics tell us about the differences?

Aluminum Bats

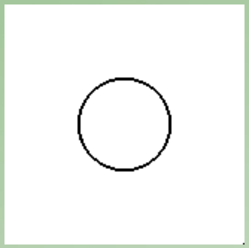
Why are aluminum bats different than wooden bats?

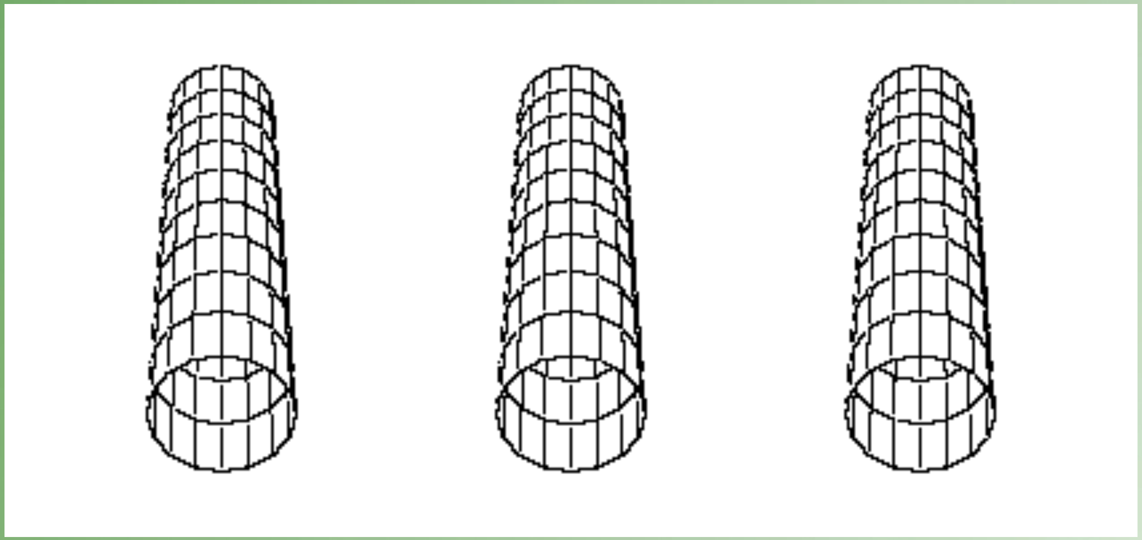
The internal vibrations of aluminum bats can be directly engineered.

MAJOR LEAGUE PHYSICS

Aluminum Bats

The hoop modes of a hollow bat





fundamental 1st overtone 2nd overtone

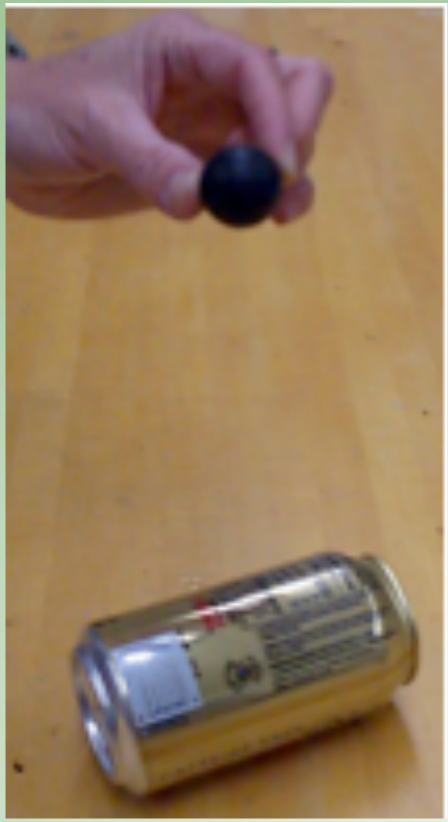
Images stolen from Dan Russell's website.

MAJOR LEAGUE PHYSICS

Aluminum Bats

Drop a “sad” ball on the table. Do you know why it is called a sad ball?

Drop the sad ball on the aluminum can. What happens?



Aluminum Bats

What have we learned?

- A wooden bat really only has transverse vibrations.
- A hollow bat can have hoop modes that can be tuned to maximize energy transfer to the ball.

MAJOR LEAGUE PHYSICS

Raffle!

MAJOR LEAGUE PHYSICS

Take Me Out to the Ball Game!

Sing along with famed Cubs announcer Harry Caray…

Take Me Out to the Ball Game!

- Take me out to the ball game.
- Take me out with the crowd.
- Buy me some peanuts and Cracker Jack.
- I don’t care if I never get back,
- cuz it’s root, root, root for the Cubbies.
- If they don’t win it’s a shame.
- For it’s one, two, three strikes, you’re out,
- At the old ball game!

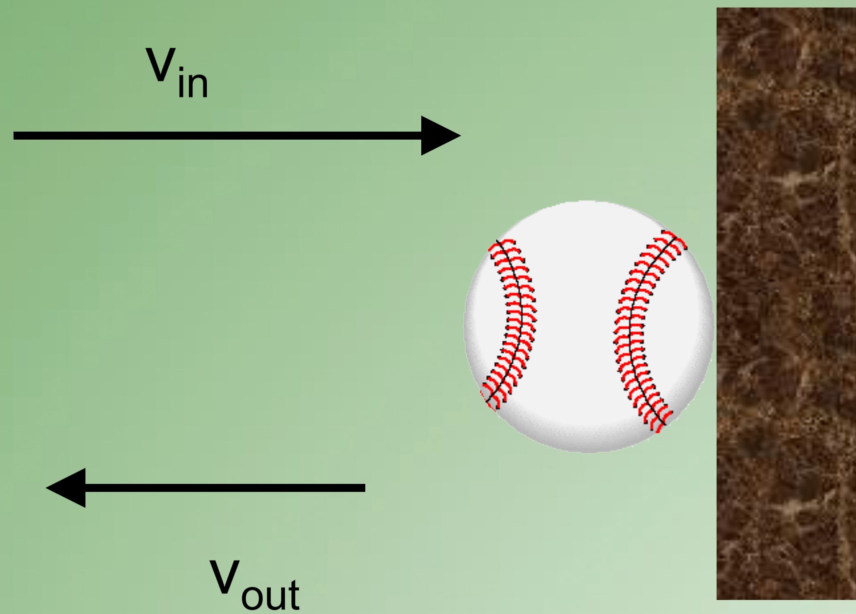
Alan Nathan’s Talk

Raffle!

MAJOR LEAGUE PHYSICS

Coefficient of Restitution

$$COR = \frac{v_{out}}{v_{in}}$$



The rules of baseball state that a ball shot at 85ft/s at a wall of northern white ash must rebound with a speed of 54.6% of the incoming speed.

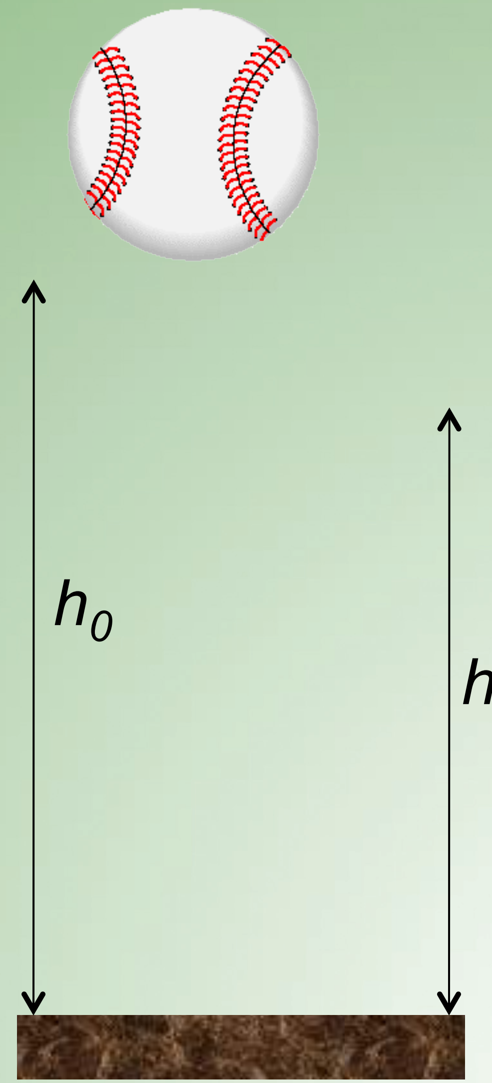
$$COR = 0.546$$

Coefficient of Restitution

$$COR = \frac{v_{out}}{v_{in}}$$

$$v_{in} = \sqrt{2gh_o} \quad v_{out} = \sqrt{2gh}$$

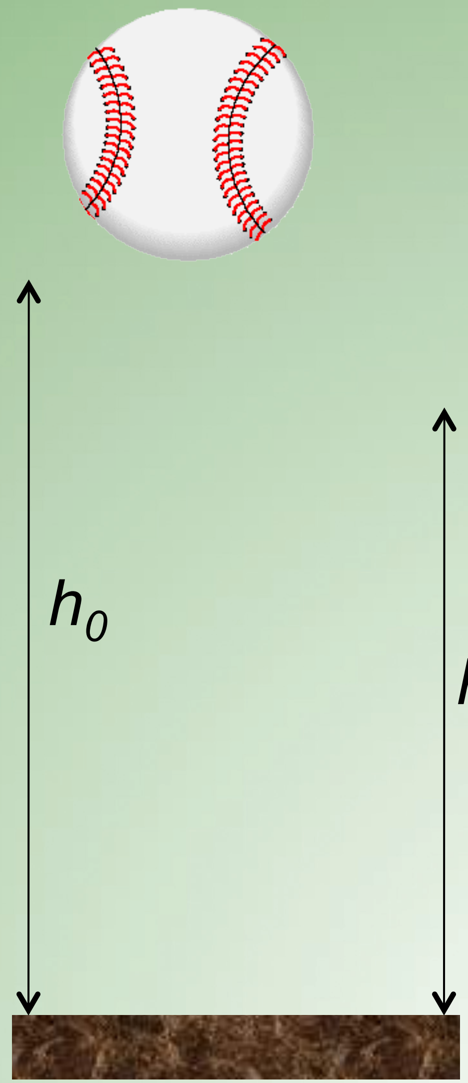
$$COR = \frac{v_{out}}{v_{in}} = \frac{\sqrt{2gh}}{\sqrt{2gh_o}} = \sqrt{\frac{h}{h_o}}$$



Coefficient of Restitution

Find the COR of the Happy Ball!

$$COR \equiv \frac{v_{out}}{v_{in}} = \sqrt{\frac{h}{h_o}}$$



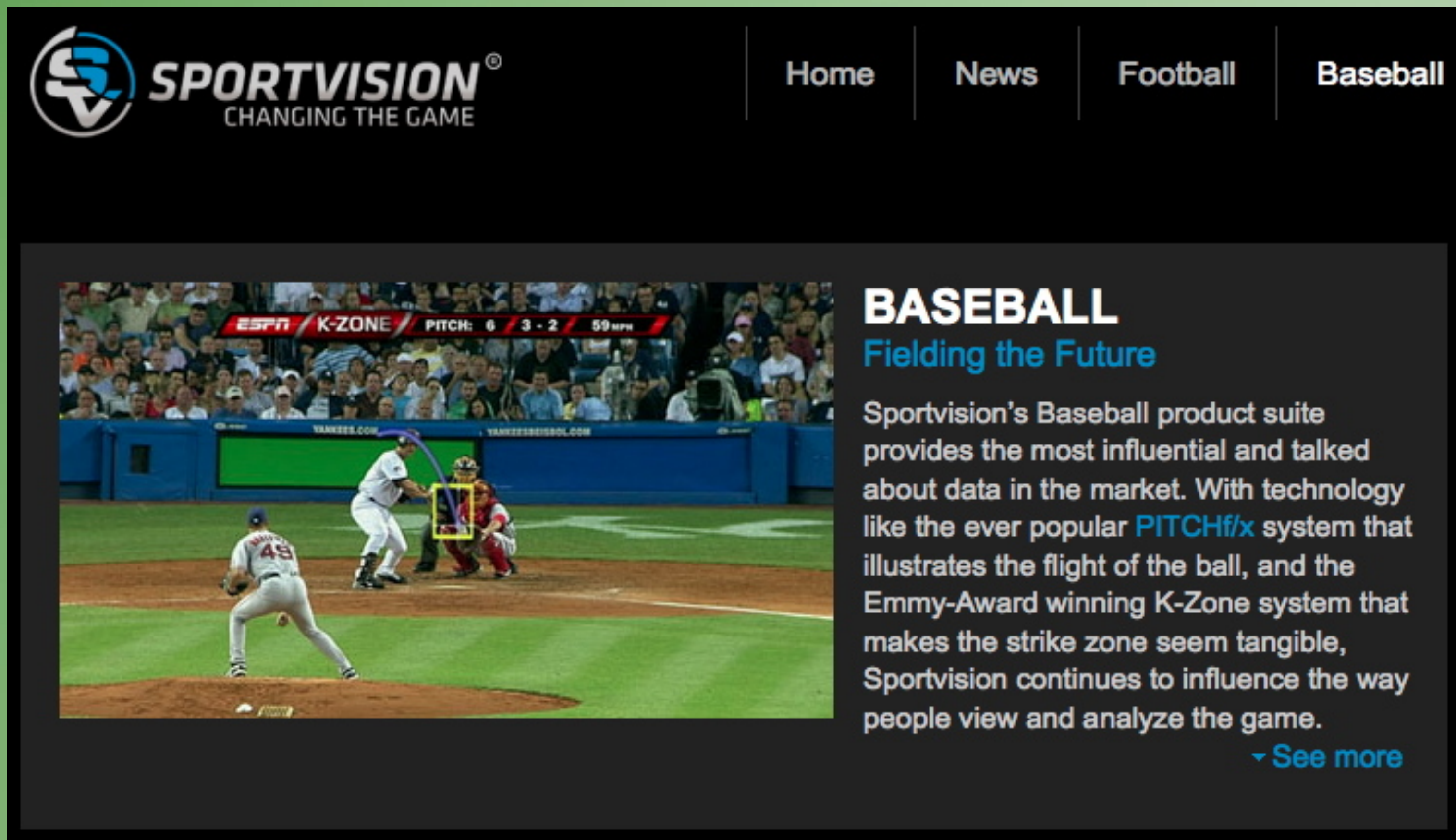
Raffle!

MAJOR LEAGUE PHYSICS

PitchFX Primer

PitchFX Primer

PitchFX Primer



PitchFX Primer

- Go to http://gd2.mlb.com/components/game/mlb/.
- Click on any year 2007 or later
- Then on the month
- Then on the day
- Then on the specific game
- Then on inning/
- Finally click on the inning you want.

MAJOR LEAGUE PHYSICS

PitchFX Primer

- You will be in a data file that looks like this:


```
<atbat num="66" b="1" s="3" o="3" start_tfs="231040" start_tfs_zulu="2012-10-29T03:10:40Z" batter="453923" stand="L"
b_height="5-11" pitcher="457435" p_throws="L" des="Gregor Blanco called out on strikes. " des_es="Gregor Blanco se poncha
sin tirarle. " event="Strikeout">
  <pitch des="Swinging Strike" des_es="Strike tirándole" id="513" type="S" tfs="231035" tfs_zulu="2012-10-29T03:10:35Z"
  x="113.30" y="136.43" sv_id="121028_231035" start_speed="95.2" end_speed="87.4" sz_top="3.02" sz_bot="1.47"
  pfx_x="5.57" pfx_z="6.13" px="-0.397" pz="2.884" x0="2.582" y0="50.0" z0="6.008" vx0="-10.157" vy0="-139.175"
  vz0="-4.906" ax="10.884" ay="32.227" az="-20.11" break_y="23.8" break_angle="-22.1" break_length="4.8" pitch_type="FT"
  type_confidence="1.000" zone="1" nasty="55" spin_dir="137.945" spin_rate="1693.730" cc="" mt=""/>
  <pitch des="Ball" des_es="Bola mala" id="514" type="B" tfs="231116" tfs_zulu="2012-10-29T03:11:16Z" x="111.59"
  y="113.98" sv_id="121028_231116" start_speed="94.9" end_speed="87.4" sz_top="3.02" sz_bot="1.47" pfx_x="4.63"
  pfx_z="7.66" px="-0.413" pz="3.938" x0="2.448" y0="50.0" z0="6.119" vx0="-9.498" vy0="-138.775" vz0="-2.866" ax="9.052"
  ay="30.197" az="-17.108" break_y="23.8" break_angle="-21.6" break_length="4.0" pitch_type="FT"
  type_confidence="1.000" zone="11" nasty="41" spin_dir="149.003" spin_rate="1837.453" cc="" mt=""/>
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  px="-0.281" pz="3.005" x0="2.52" y0="50.0" z0="6.055" vx0="-8.914" vy0="-139.151" vz0="-5.226" ax="6.654" ay="30.259"
  az="-17.423" break_y="23.8" break_angle="-14.5" break_length="3.9" pitch_type="FT" type_confidence="1.000" zone="1"
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  <pitch des="Called Strike" des_es="Strike cantado" id="516" type="S" tfs="231216" tfs_zulu="2012-10-29T03:12:16Z"
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  pfx_x="-1.23" pfx_z="-5.73" px="-0.386" pz="1.852" x0="2.694" y0="50.0" z0="6.122" vx0="-6.94" vy0="-121.09"
  vz0="-1.632" ax="-1.807" ay="26.673" az="-40.497" break_y="23.8" break_angle="4.4" break_length="11.4"
  pitch_type="CU" type_confidence=".901" zone="7" nasty="30" spin_dir="347.752" spin_rate="1020.412" cc="" mt=""/>
</atbat>
```


MAJOR LEAGUE PHYSICS

PitchFX Primer

- A single pitch looks like this:


```
<pitch des="Foul" des_es="Foul" id="507" type="S" tfs="230849"
tfs_zulu="2012-10-29T03:08:49Z" x="109.01" y="132.11" sv_id="121028_230849"
start_speed="94.4" end_speed="86.0" sz_top="3.32" sz_bot="1.53" pfx_x="8.23" pfx_z="10.3"
px="-0.315" pz="2.919" x0="2.562" y0="50.0" z0="6.035" vx0="-10.7" vy0="-137.956"
vz0="-6.156" ax="15.708" ay="33.556" az="-12.449" break_y="23.7" break_angle="-43.3"
break_length="4.1" pitch_type="FF" type_confidence=".676" zone="1" nasty="41"
spin_dir="141.469" spin_rate="2651.720" cc="" mt=""/>
```


MAJOR LEAGUE PHYSICS

PitchFX Primer

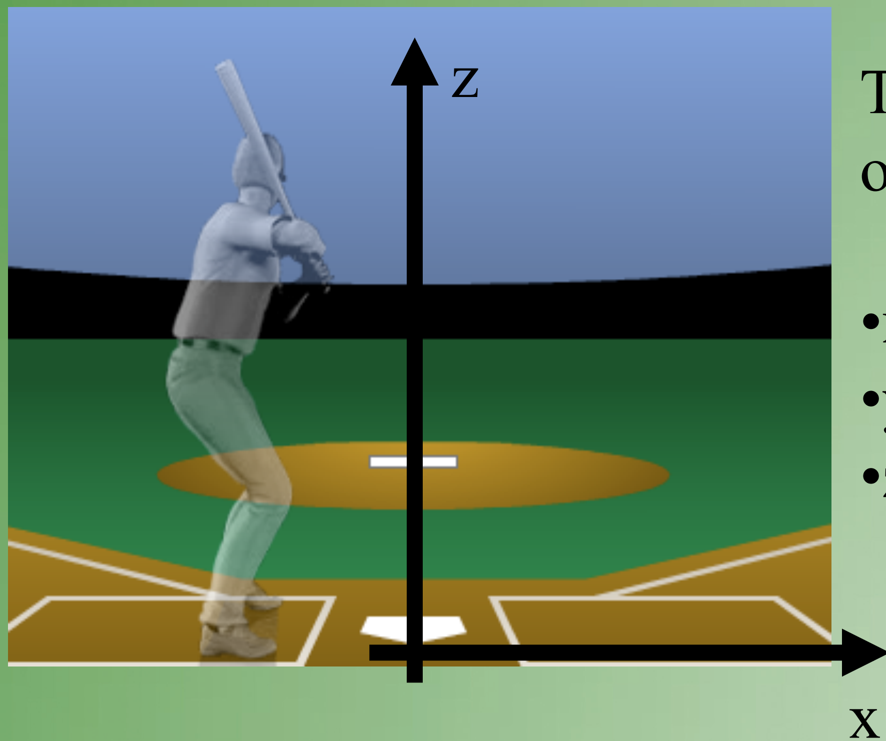
- A single pitch looks like this:


```
<pitch des="Foul" des_es="Foul" id="507" type="S" tfs="230849"
tfs_zulu="2012-10-29T03:08:49Z" x="109.01" y="132.11" sv_id="121028_230849"
start_speed="94.4" end_speed="86.0" sz_top="3.32" sz_bot="1.53" pfx_x="8.23" pfx_z="10.3"
px="-0.315" pz="2.919" x0="2.562" y0="50.0" z0="6.035" vx0="-10.7" vy0="-137.956"
vz0="-6.156" ax="15.708" ay="33.556" az="-12.449" break_y="23.7" break_angle="-43.3"
break_length="4.1" pitch_type="FF" type_confidence=".676" zone="1" nasty="41"
spin_dir="141.469" spin_rate="2651.720" cc="" mt=""/>
```


- The kinematic data can be extracted:

Quantity	Value	Units	Description
start_speed	94.4	mph	speed at y0=50ft
end_speed	86.0	mph	speed at the front of home plate y=1.417ft
px	-0.315	ft	x-position at the front of home plate
pz	2.919	ft	z-position at the front of home plate
x0	2.562	ft	x-position at y=50ft
y0	50.0	ft	arbittrary fixed initial y-position
z0	6.035	ft	z-position at y=50ft
vx0	-10.7	ft/s	x-velocity at y=50ft
vy0	-137.96	ft/s	y-velocity at y=50ft
vz0	-6.156	ft/s	z-velocity at y=50ft
ax	15.708	ft/s/s	x-acceleration assumed constant
ay	33.556	ft/s/s	y-acceleration assumed constant
az	-12.449	ft/s/s	z-acceleration assumed constant

PitchFX Primer



The origin is at the back point of home plate.

•x-axis - to the catcher's right
•y-axis - toward the pitcher
•z-axis - vertically upward

MAJOR LEAGUE PHYSICS

Raffle!

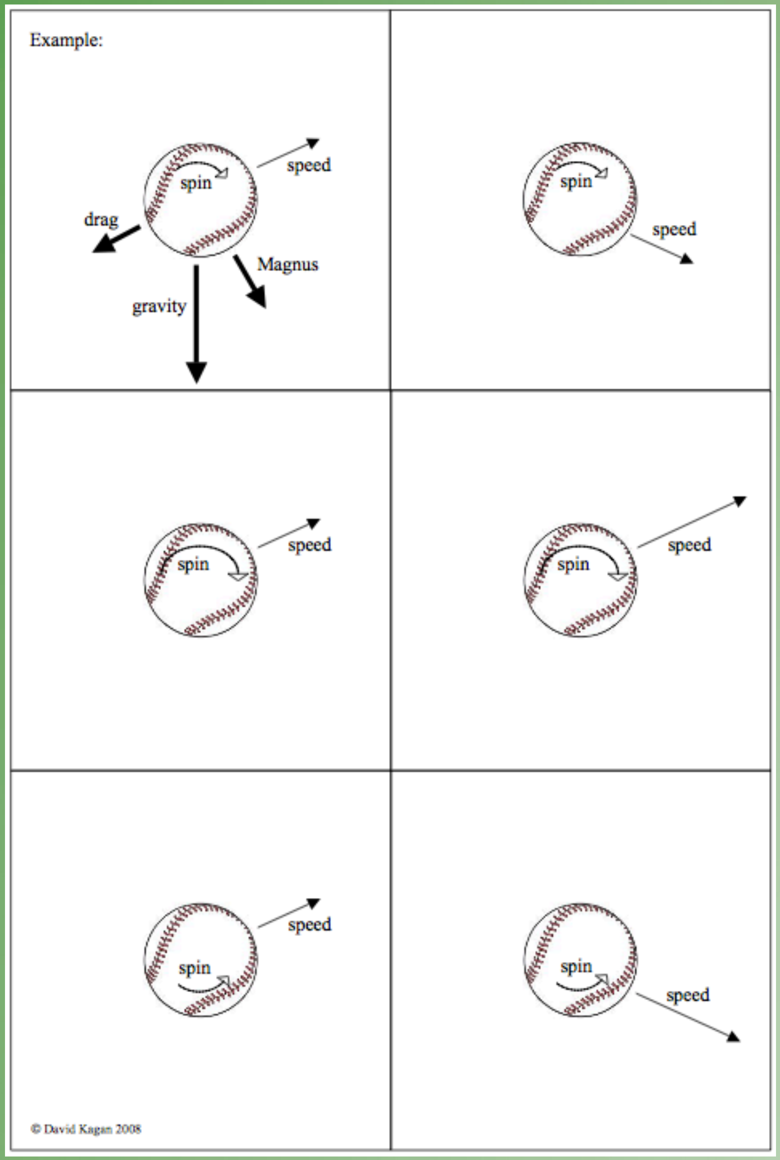
MAJOR LEAGUE PHYSICS

Curve Balls

Curve Balls

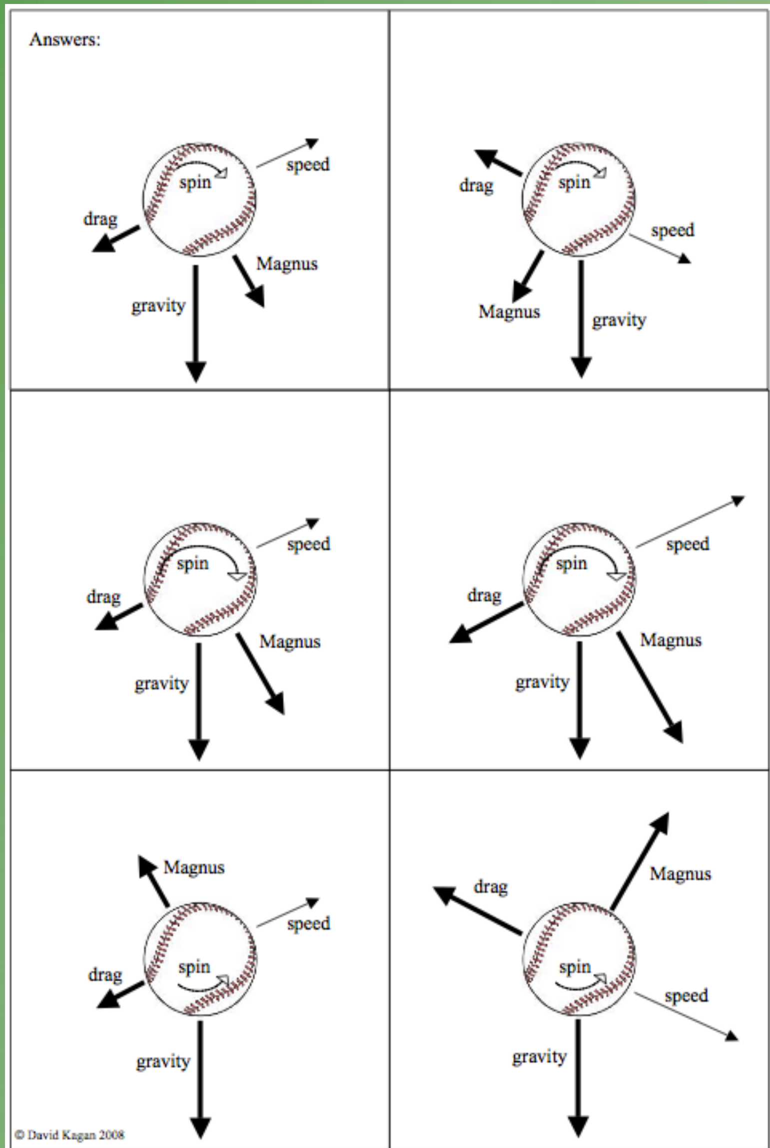
- Magnus Effect with a falling balloon

Curve Balls



MAJOR LEAGUE PHYSICS

Curve Balls



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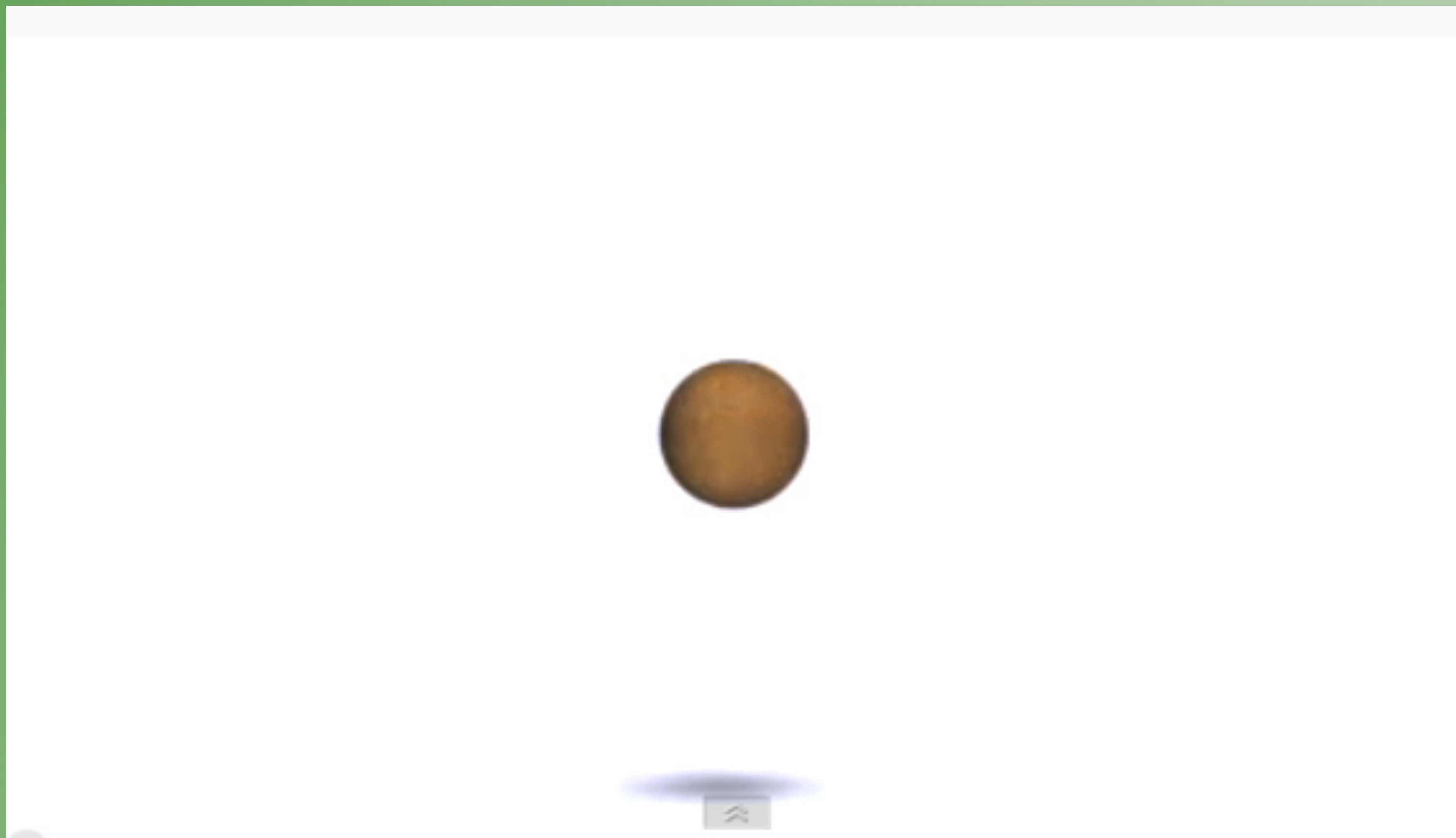
Curve Balls

- Why does a curve ball curve?



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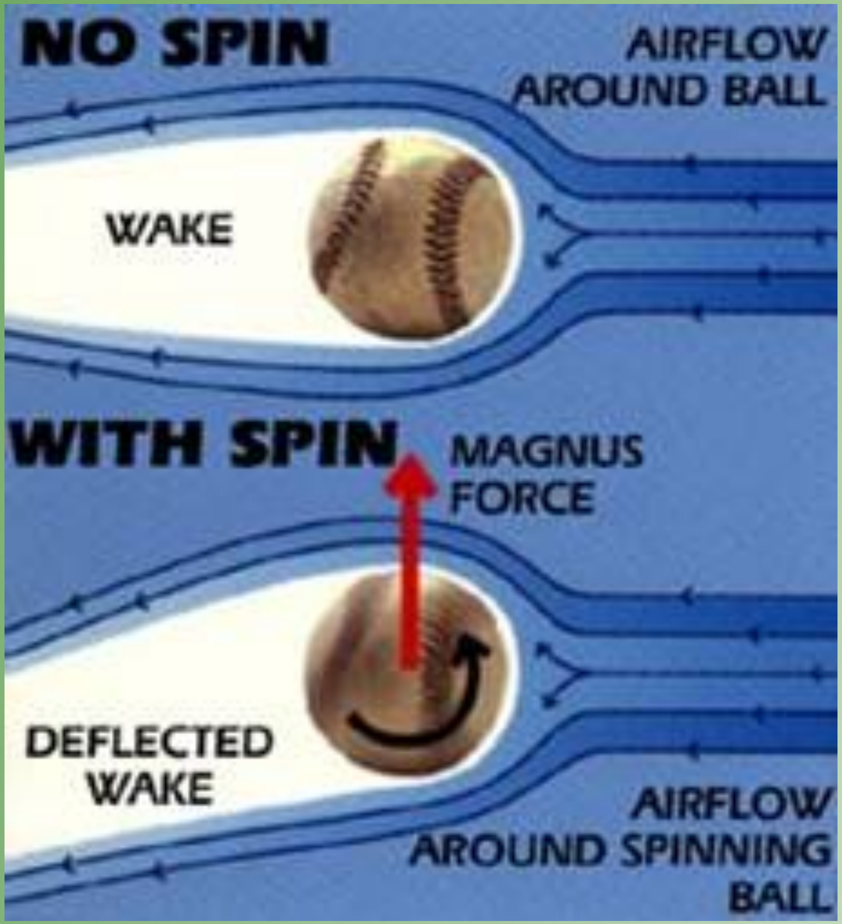
Curve Balls

- Why does a curve ball curve?

MAJOR LEAGUE PHYSICS

Curve Balls

- Why does a curve ball curve?
- My preferred explanation…



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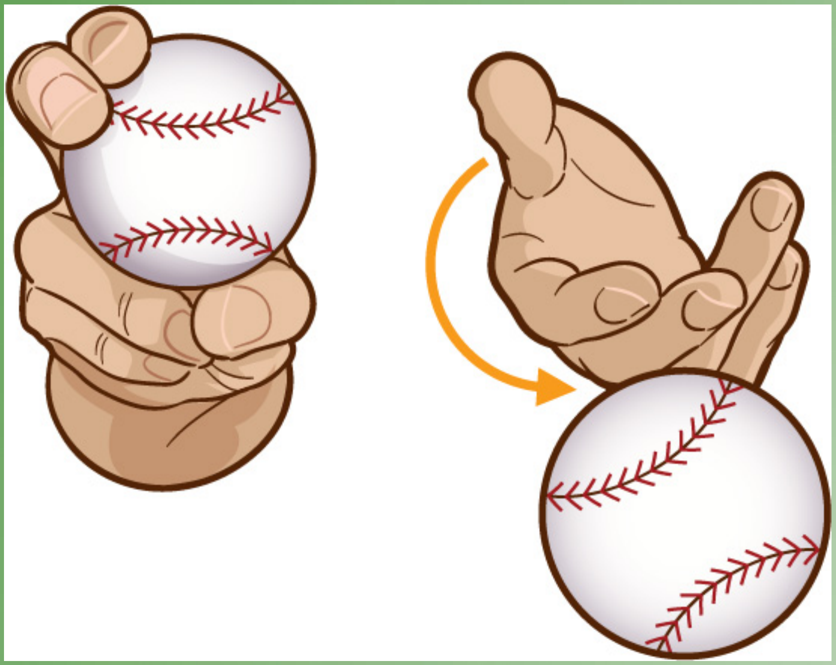
Curve Balls

- teach curve balls with styrofoam balls



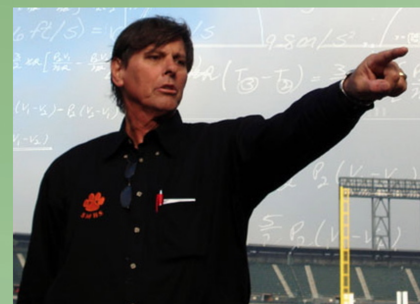
MAJOR LEAGUE PHYSICS

Raffle!

MAJOR LEAGUE PHYSICS

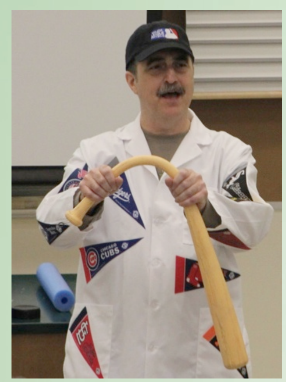
Web Site Tours

- laserpablo.com



- webusers.npl.illinois.edu/~a-nathan/pob/

- MajorLeaguePhysics.org



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