Major League Physics

Using Baseball to Teach Mechanics

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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
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7. Coefficient of Restitution
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Raffle!
Baseball on Mars

NASA FINALLY RUNS OUT OF IDEAS FOR MISSIONS
Baseball on Mars

Atwood’s Machine

\[ F_{\text{net}} = ma \]

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

\[ \frac{mg}{2} = \frac{3}{2} ma \]

\[ a = \frac{g}{3} \]
Baseball on Mars

Build the “Baseball on Mars” Atwood’s Machine!
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?
Properties of a Baseball Bat

The center of mass (CM)

Where is the CM of a real bat?
Properties of a Baseball Bat

The center of mass (CM)

CM in the middle

29cm

CM is closer to the barrel end
Properties of a Baseball Bat

The center of mass (CM)

Cardstock bats
Raffle!
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?
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?
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 \( T = 2\pi \sqrt{\frac{I}{m r_{cm}}} \)

So, \[ I = m r_{cm} \frac{T^2}{4\pi^2} \] given \( m = 144\text{g} \)

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

Did you get \( I = 0.013\text{kg}\cdot\text{m}^2 \) ?
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?
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

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

\[ \sqrt{\frac{r_{co}}{g}} = \sqrt{\frac{I}{mgr_{cm}}} \Rightarrow \frac{r_{co}}{g} = \frac{I}{mgr_{cm}} \Rightarrow I = mr_{co}r_{cm} \]
The center of percussion (CP)

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

Second Law for Rotation

\[ \sum \tau = I \alpha \]

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.

\[ I = m r_{cp} r_{cm} \]
Homers and the Bull’s Eye Apparatus
Homers and the Bull’s Eye Apparatus
Homers and the Bull’s Eye Apparatus
Homers and the Bull’s Eye Apparatus

\[ d = 20cm \]

\[ t_{\text{gate}} = \text{photogate time} \]

\[ h = \frac{1}{2} gt_{\text{top}}^2 \]

\[ t_{\text{top}} = \sqrt{\frac{2h}{g}} \]

\[ v_x = \frac{d}{t_{\text{gate}}} \]

\[ d_x = v_x t_{\text{top}} \]
Homers and the Bull’s Eye Apparatus
Homers and the Bull’s Eye Apparatus

$t_{\text{top}}$

$t_{\text{total}} = 2\ t_{\text{top}}$
Homers and the Bull’s Eye Apparatus

d_{\text{homer}} = v_x \left( 2 \ t_{\text{top}} \right)

t_{\text{total}} = 2 \ t_{\text{top}}
Raffle!
Ball-Bat Collisions

High Speed Camera during the 2012 Playoffs
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)
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.
Ball-Bat Collisions

Vibrational Nodes (VN)

You can demonstrate vibrational nodes with a flexible stick.
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 $\frac{3}{4}$ of the way down the bat.

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

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!
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.
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!
Aluminum Bats

Bats have evolved over time.
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?
Why are aluminum bats different than wooden bats?

The internal vibrations of aluminum bats can be directly engineered.
Aluminum Bats

The hoop modes of a hollow bat

fundamental  1st overtone  2nd overtone

Images stolen from Dan Russell’s website.
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?
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.
Raffle!
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
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!

\[ COR \equiv \frac{v_{\text{out}}}{v_{\text{in}}} = \sqrt{\frac{h}{h_0}} \]
Raffle!
PitchFX Primer
PitchFX Primer
BASEBALL
Fielding the Future

Sportvision’s Baseball product suite provides the most influential and talked about data in the market. With technology like the ever popular PITCHf/x system that illustrates the flight of the ball, and the Emmy-Award winning K-Zone system that makes the strike zone seem tangible, Sportvision continues to influence the way people view and analyze the game.

See more
• 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.
PitchFX Primer

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

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<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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PitchFX Primer

- A single pitch looks like this:

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<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=""/>
```
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:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>start_speed</td>
<td>94.4</td>
<td>mph</td>
<td>speed at y0=50ft</td>
</tr>
<tr>
<td>end_speed</td>
<td>86.0</td>
<td>mph</td>
<td>speed at the front of home plate y=1.417ft</td>
</tr>
<tr>
<td>px</td>
<td>-0.315</td>
<td>ft</td>
<td>x-position at the front of home plate</td>
</tr>
<tr>
<td>pz</td>
<td>2.919</td>
<td>ft</td>
<td>z-position at the front of home plate</td>
</tr>
<tr>
<td>x0</td>
<td>2.562</td>
<td>ft</td>
<td>x-position at y=50ft</td>
</tr>
<tr>
<td>y0</td>
<td>50.0</td>
<td>ft</td>
<td>arbitrary fixed initial y-position</td>
</tr>
<tr>
<td>z0</td>
<td>6.035</td>
<td>ft</td>
<td>z-position at y=50ft</td>
</tr>
<tr>
<td>vx0</td>
<td>-10.7</td>
<td>ft/s</td>
<td>x-velocity at y=50ft</td>
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<tr>
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<tr>
<td>vz0</td>
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<td>ft/s</td>
<td>z-velocity at y=50ft</td>
</tr>
<tr>
<td>ax</td>
<td>15.708</td>
<td>ft/s/s</td>
<td>x-acceleration assumed constant</td>
</tr>
<tr>
<td>ay</td>
<td>33.556</td>
<td>ft/s/s</td>
<td>y-acceleration assumed constant</td>
</tr>
<tr>
<td>az</td>
<td>-12.449</td>
<td>ft/s/s</td>
<td>z-acceleration assumed constant</td>
</tr>
</tbody>
</table>
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
Curve Balls

DRAG FORCE
Curve Balls

- Magnus Effect with a falling balloon
Curve Balls
Curve Balls

Answers:

1. Drag
2. Spin
3. Speed
4. Gravity
5. Magnus

Drag: Magnus

Gravity: Magnus

Spin: Magnus

Speed: Magnus

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MAJOR LEAGUE PHYSICS
Curve Balls

• Why does a curve ball curve?
Curve Balls

- Why does a curve ball curve?
Curve Balls

• Why does a curve ball curve?
• My preferred explanation…
Curve Balls

• teach curve balls with styrofoam balls
Raffle!
Web Site Tours

- laserpablo.com
- webusers.npl.illinois.edu/~a-nathan/pob/
- MajorLeaguePhysics.org