Day 4

Physics of Sports

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http://pages.jh.edu/~maliyou1/Physics_of_Sports/

Image https://www.disneyclips.com/imagesnewb/skating.html

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Plan for Today

- Part 1: Finish the discussion about <u>forces</u> we had started in the last class:
  - Curveballs, Foul Shots, and Bent Kicks
- Part 2: Energy in Sports: Bursts of Power
  - Baseball
  - Ping Pong

Part 1: Curveballs, Foul Shots, and Bent Kicks

Buoyancy

- The water in a pool pushes up on a person with a force equal to the weight of the volume of water that the person's body displaces.

$$\boxed{|\vec{F}_B| = |\vec{W}_{\text{displaced H}_2\text{O}}| = \left(\rho_{\text{H}_2\text{O}}\right)\left(V_{\text{displaced H}_2\text{O}}\right) g}$$

Lisa, Michael. *The Physics of Sports*. McGraw-Hill Higher Education, 20150220. VitalBook file.

Buoyancy in Air

Rather than a constant downward acceleration of $-g$, the (still constant) acceleration becomes

$$a_y = \left(1 - \frac{|\vec{F}_B|}{|\vec{W}|}\right)(-g)\,.$$

This reduced value replaces $-g$ in kinematic formulas

Recall that the ratio of forces for a basketball is about 1.5%

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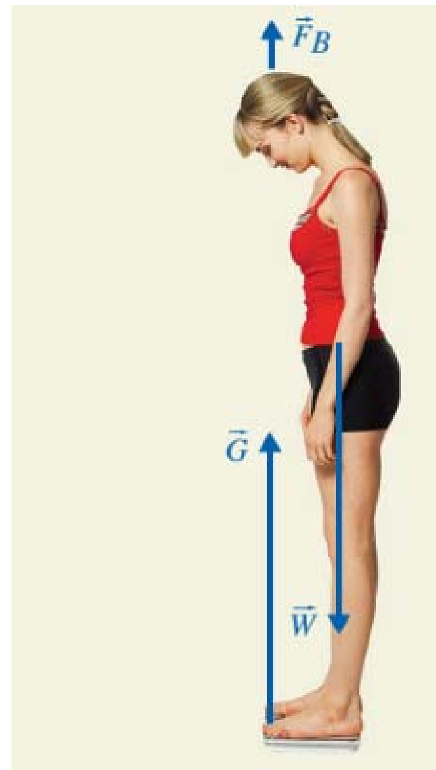
Interesting fact – weight loss??

- What do you get if you subtract the following from the weight of your body?

$$|\vec{F}_B| = |\vec{W}_{\text{displaced H}_2\text{O}}| = \left(\rho_{\text{H}_2\text{O}}\right)\left(V_{\text{displaced H}_2\text{O}}\right) g$$



(© Stockbyte/Getty Images RF)

- Q. Here we will justify the statement: The density of a human body depends on the fraction of fat composing the body, since fat is less dense than muscle. (Human fat tissue has a density of about 0.9 kg/liter (900 kg⁄m3), so fat floats. Meanwhile the density of fat-free tissue is about 1.1kg/liter (1100 kg⁄m3), so this tissue sinks.)
- Consider two males, both 180 lb. One is a typical American physics professor, who shall go unnamed. With 18% body fat, the density of his body is 1.81 slug⁄ft^3.
  - (a) What is the volume of his body?
  - (b) What is the buoyant force on the professor under water? If he jumps off a 10-m platform, he hits the water at 45.7 ft/s (31.2 mph).
  - (c) If you consider buoyancy and gravity alone (that is, ignoring drag), will the water eventually bring him to rest?
  - (d) If so, how far will he travel in the water before coming to rest?
- The other 180-lb male is Michael Phelps, with a reported 6% body fat, the minimum “essential” fat without being considered medically ill. The mass density of Michael’s body is 1.98 slug⁄ft^3.
  - (e) What is Michael’s body volume?
  - (f) What is the buoyant force on Michael under water?
  - (g) If you consider buoyancy and gravity alone (that is, ignoring drag), will the water eventually bring him to rest?
  - (h) If so, how far will he travel in the water before coming to rest?

Problem 1, Chapter 5, Lisa, Michael. *The Physics of Sports*. McGraw-Hill Higher Education, 20150220. VitalBook file.

Drag: Moving through Fluids

This leads to a reasonable expectation for the drag force formula:

$$|\vec{F}_D| \propto (A\rho v) \cdot v \rightarrow \boxed{|\vec{F}_D| = \frac{C_D}{2} A\rho v^2}. \quad (5.4)$$

Here, C_D is the **drag coefficient** or drag constant. Like the friction coefficients, this constant has to be measured experimentally. Table B.6 in appendix B lists various drag coefficients.

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Table B.6. Some typical drag coefficients. These will vary somewhat with surface roughness and speed. Online tables abound; most of these are from http://www.engineeringtoolbox.com/drag-coefficient-d_627.html

Object	C_D
Smooth sphere (low speeds)	0.47
Solid hemisphere	0.42
Solid hemisphere flow normal to flat side	1.17
Bike racer	0.88
Upright person, wind in face	1.0–1.3
Ski jumper	1.2–1.3
Head-down skydiver	0.4–0.6
Dolphin	0.0036
Tractor trailer truck	0.96
Model-T Ford	0.8
Toyota Prius	0.26

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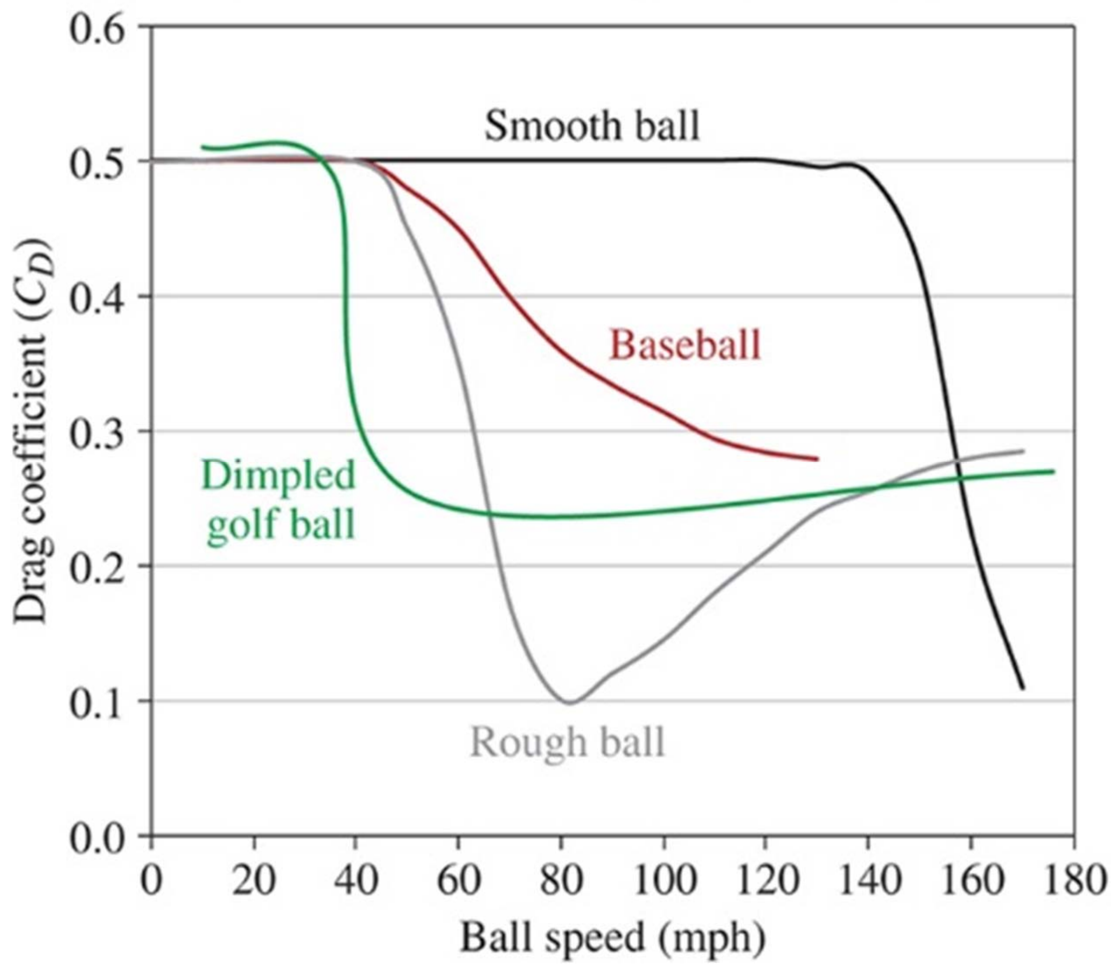
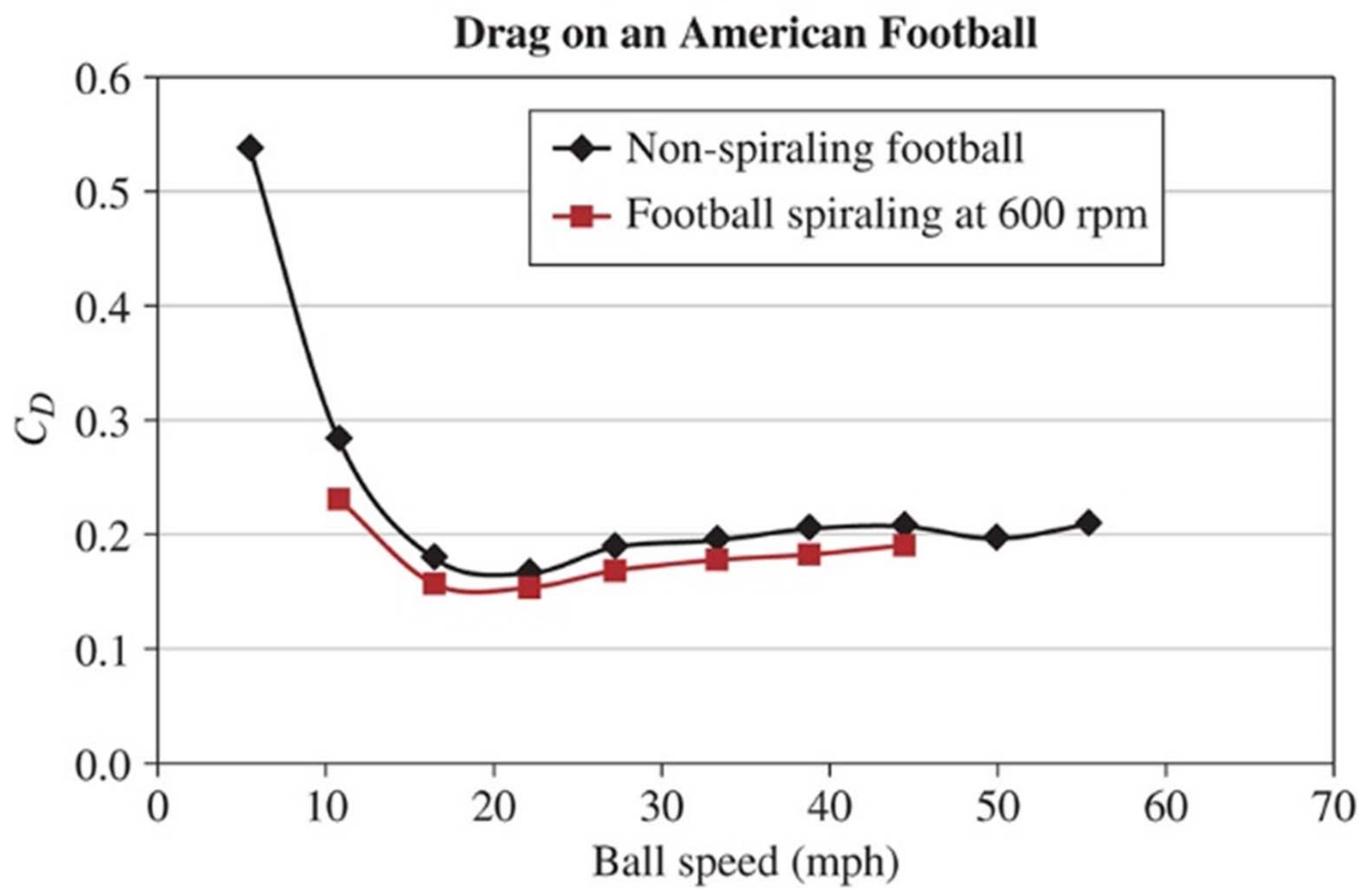
Important complication 1: C_D depends on speed

Notice the average value of drag coefficient for low speeds.
These are all spherical!

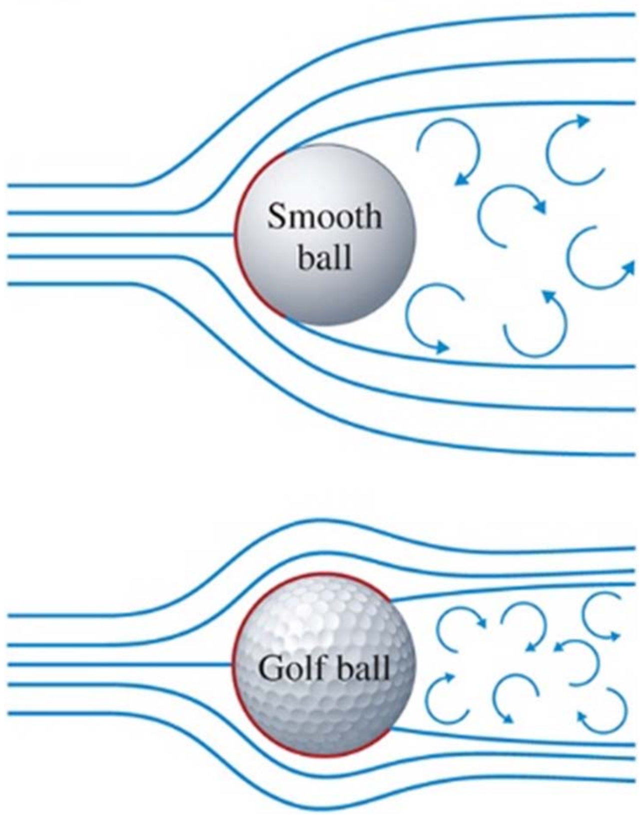




Wind tunnel measurements of the drag coefficient for an American football flying nose first into the air. Based on data from R. G. Watts and G. Moore, American Journal of Physics 71: 791 (2003).

Important complication 2: C_D depends on surface roughness

- Irregularities on the surface of a golf ball trip turbulent behavior in the surface layer, leading to a smaller wake and lower drag force than a smooth ball traveling at the same speed.



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Bending a ball’s flight, the Magnus effect

- Conclusion: Aerodynamics is complicated
- Let’s watch
- The Physics Behind a Curveball - The Magnus Effect
- https://youtu.be/YIPO3W081Hw?t=15s
- How to curve a ball backwards using science,
- https://www.youtube.com/watch?v=akjQbPKKD7I

Bending a ball's flight, the Magnus effect (cont.)

- The magnitude of the Magnus force is given by a formula similar to the drag formula:

$$|\vec{F}_M| = \pi C_M \rho_{\text{air}} R A v f$$

$$|\vec{F}_M| = \pi^2 C_M \rho_{\text{air}} R^3 v f \quad \text{for a spherical ball}$$

Another Numerical

Q. We have discussed how, if there were only the Magnus force, a curveball would follow a circular path.

(a) For a typical pitch, what would be the radius of its circular path?

(b) In this unrealistic but interesting case, the pitcher could pitch the ball and then turn around and catch the ball he'd just thrown! How much time would pass between his pitch and his catch?

Sol: v=85mph

f=10rps

Search internet for the remaining variables!

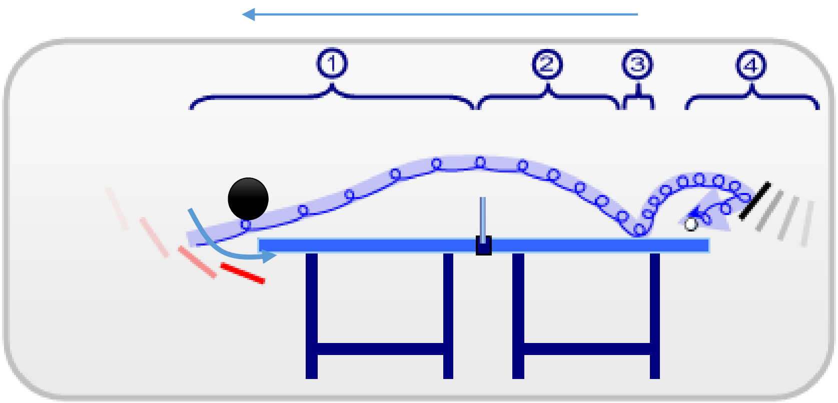
$$r = \left(\frac{m}{\pi C_M \rho_{\text{air}} A R f}\right) \cdot v$$

Problem 12, Chapter 5. Lisa, Michael. *The Physics of Sports*. McGraw-Hill Higher Education, 20150220. VitalBook file.

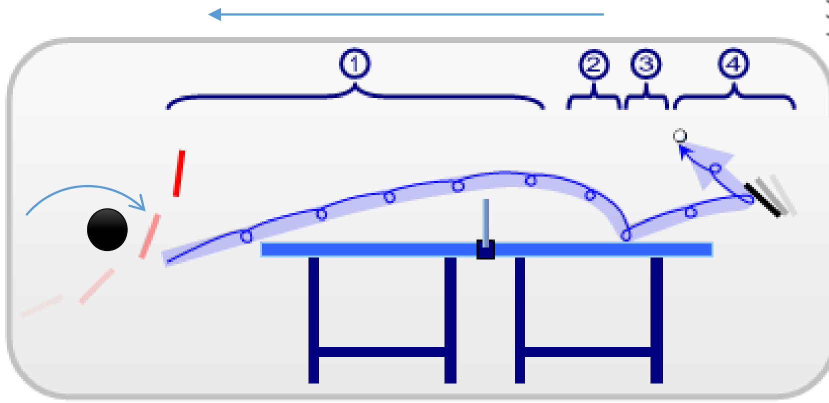
Group work (30 minutes)
Estimating Magnus Force

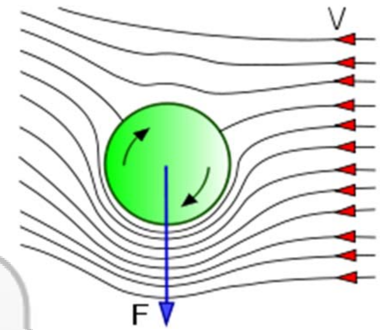
1. Material: Available on the teacher's desk + video camera + tracker software
2. Procedure:
   - Form groups (need not be your project groups)
   - Pick a paper and create a rolled surface/cylinder
   - Drop it from a certain height, making sure you can see Magnus effect
   - Record a few short videos of the drop to measure height (or velocity)
3. Analysis: Estimate the magnitude of the Magnus force
4. Report: Collect all information into a sheet and submit (including your names, ball(s) used, surface(s) used, etc.

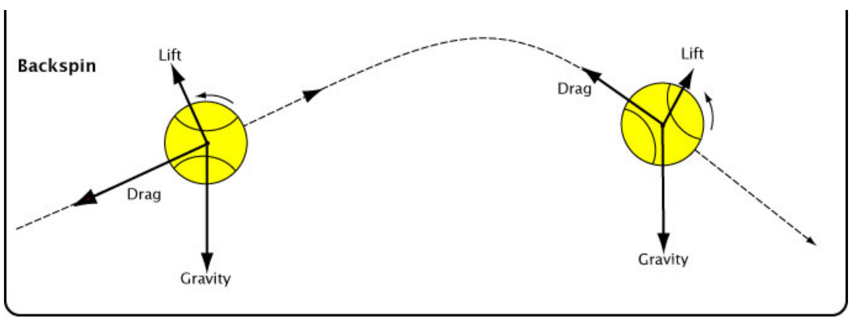
4 phases in a backspin curve

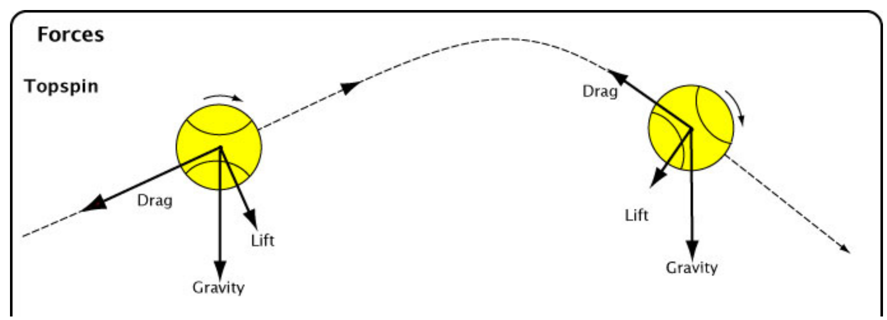


4 phases in a topspin curve



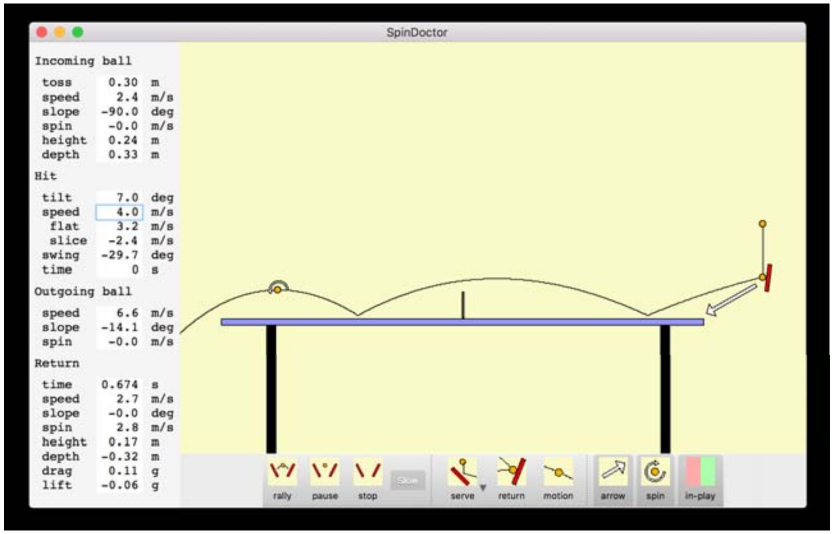






https://en.wikipedia.org/wiki/Table_tennis

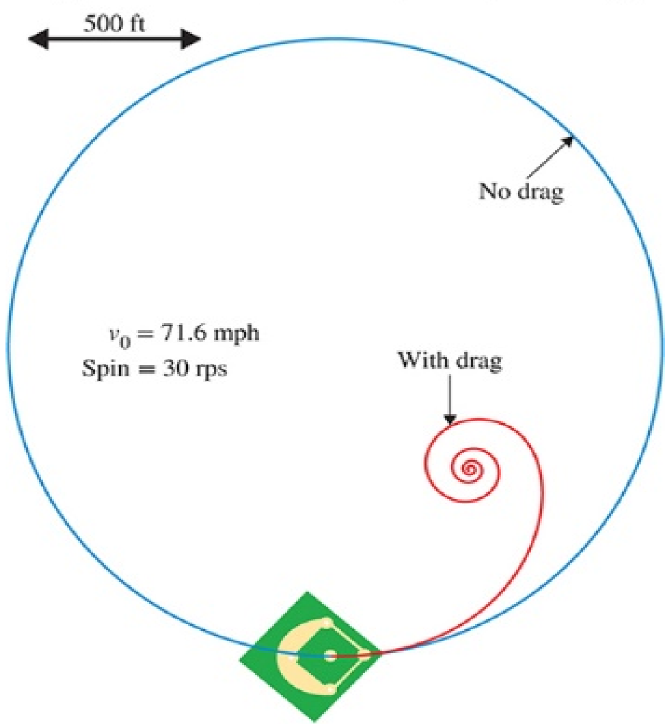
- Killerspin Table Tennis Technique: Ball and Spin, https://www.youtube.com/watch?v=O2vrVwjqktg
- Spin Doctor: A ping pong physics simulation (only for Mac):
- http://sonic.net/~goddard/home/spin/docs/spin.html



We can even find the radius of the circular path, which we call r:

$$\left.\begin{array}{ll} \text{equation 3.17:} & |\vec{F}_M| = m\frac{v^2}{r} \\ \text{equation 5.6:} & |\vec{F}_M| = \pi C_M \rho_{\text{air}} R A v f \end{array}\right\} \rightarrow r = \left(\frac{m}{\pi C_M \rho_{\text{air}} A R f}\right) \cdot v$$

We take C_M=1 for most calculations



Let’s discuss your projects

Kristyn	Baseball
Michael L	Baseball
Tim	Baseball
Julian	Basketball
Ryan R	Basketball
Craig	Basketball
Tori	Ice Hockey
Andrew	Pole vaulting
Raymond	Taekwondo
Theophile	Tennis
Michael J	Tennis

Day 4 Material
Energy in Sports: Bursts of Power

Objective:

- Sports is all about controlling the flow of energy from one form to another, beginning with the food we eat and the air we breathe.
- This lecture covers the five forms of energy relevant to sports, with a focus on quick bursts of energy conversion.
- Along the way, we’ll discuss the human engine and the concepts of efficiency and power.

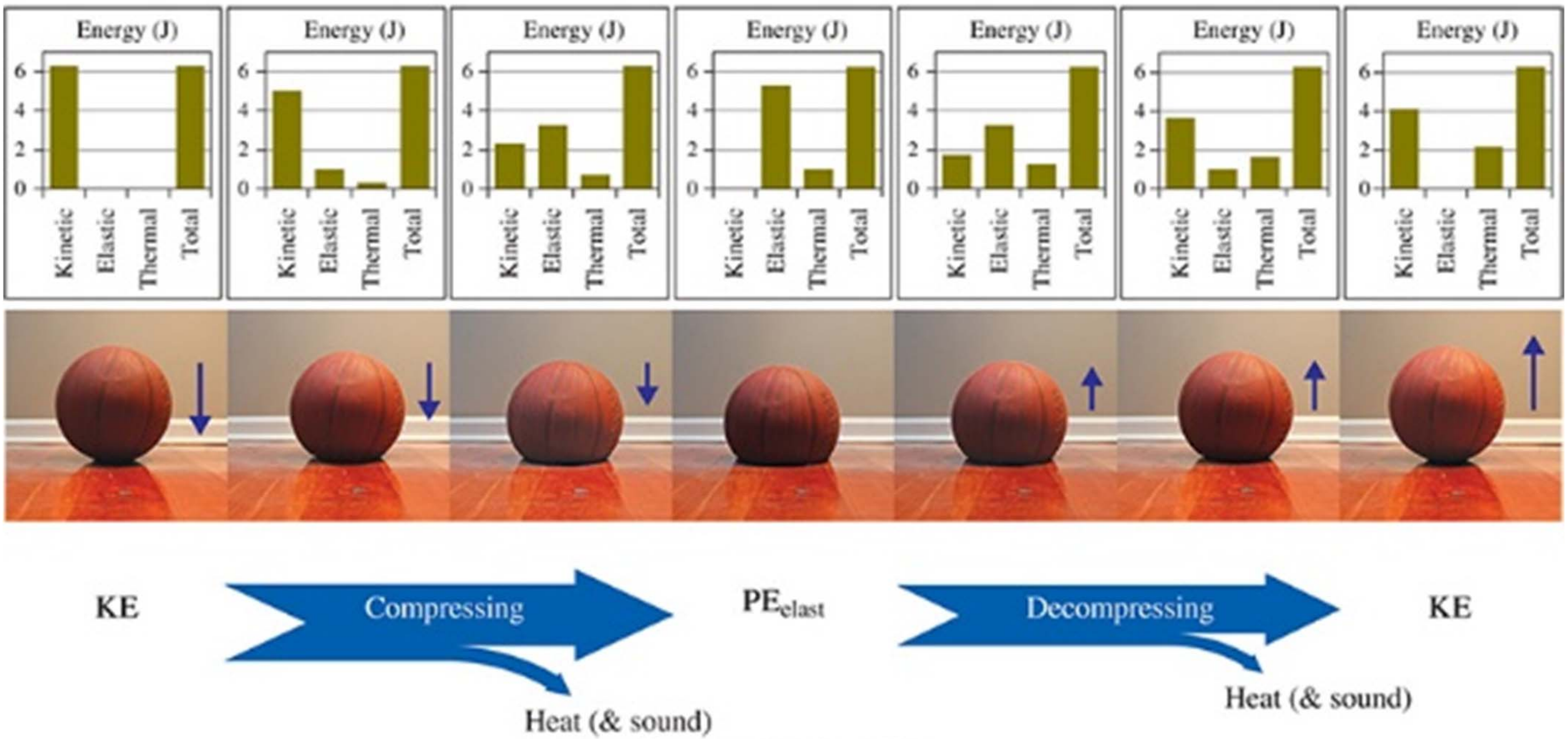


Photo courtesy of Mike Lisa

Following the energy during the bounce: As a basketball bounces on the floor, energy is transformed between kinetic, elastic, and thermal forms. The small changes in gravitational potential energy aren't plotted, to reduce clutter. The ball's changing velocity is shown by the small arrows. (A somewhat deflated ball was used in this image, to emphasize the compression.) (Photo courtesy of Mike Lisa).

Efficiency

$$\eta = \frac{\text{useful energy output from the process}}{\text{total energy input to the process}}$$

- Also note that, Physicists and sports equipment manufacturers use the coefficient of restitution (COR) *e* to classify collisions. It is simply the ratio of the separation speed to the approach speed:

$$e = -\frac{v_{\text{rel,after}}}{v_{\text{rel,before}}}$$

$$\text{bouncing vertically on floor:} \quad e = \sqrt{\frac{h_f}{h_i}}$$

The efficiency of a basketball bounce

Here it seems pretty obvious that the "input" energy is the ball's kinetic energy just as it hits the floor, and the "useful output" is its kinetic energy as it leaves the floor.

$$\eta_{\text{basketball bounce}} = \frac{\text{KE}_{\text{after}}}{\text{KE}_{\text{before}}} = \frac{\frac{1}{2}mv_{\text{after}}^2}{\frac{1}{2}mv_{\text{before}}^2} = \left(\frac{v_{\text{after}}}{v_{\text{before}}}\right)^2 .$$

The nice thing is that we know how the velocities before and after the bounce are related, through the coefficient of restitution from equation 6.18: $v_{\text{after}} = ev_{\text{before}}$, so we can write

$$\eta_{\text{basketball bounce}} = e^2 = \underbrace{0.81^2 = 0.66}_{\substack{\text{NBA leather ball} \\ \text{from section 6.4.1}}}.$$

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Group work (30 minutes)
Different balls and efficiency estimates

1. Material: Available on the teacher's desk + video camera + tracker software
2. Procedure:
   - Form groups (need not be your project groups)
   - Pick a ball
   - Decide a surface to drop the ball
   - Record a few short videos of the drop to measure height (or velocity)
3. Analysis: Find efficiency of the ball(s)
4. Data: Collect all information into a sheet and submit (including your names, ball(s) used, surface(s) used, etc.

Open-Ended Work

- Search for a video of your favorite sport which you can analyze using "Tracker".
- What to watch for: clarity of video, plane of recording, fps, method of setting scale, etc.
- Once you have selected a video, you can download using keepvid.com
- Now open it in Tracker and analyze
- Check JHU athletics for better quality videos