Teaching Introductory Physics in Biological Context

Catherine H. Crouch, Swarthmore College

Univ of Pittsburgh/CMU Physics Colloquium

25 February 2013

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Today’s talk

- What is “physics in biological context”?
- Why develop new introductory physics for life sciences (IPLS) courses?
- Swarthmore’s IPLS: design process and implementation
- Assessment
- Future directions

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Collaborators and colleagues

- Fai Wisittanawat ’13 and Ann Renninger (Swat)
- Ken Heller and Robin Wright (Univ. of Minnesota)
- University of Maryland NEXUS group: Joe Redish, Todd Cooke, Karen Carleton, Wolfgang Losert, Vashti Sawtelle, Chandra Turpen, Julia Svoboda, Kristi Hall, Ben Geller, Ben Dreyfus ….
- Tim McKay (University of Michigan)
- Mark Reeves and Rob Donaldson (GWU)
- Suzanne Amador Kane (Haverford)
- Dawn Meredith (University of New Hampshire)
- …. And many more!

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Physics in biological context

- Earthworms absorb oxygen by diffusion through their skin. What limits does this impose on their shape and size?

From University of Maryland NEXUS team

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Physics in biological context

- Why does reducing heart valve cross-sectional area by half lead to a >93% reduction in blood flow?

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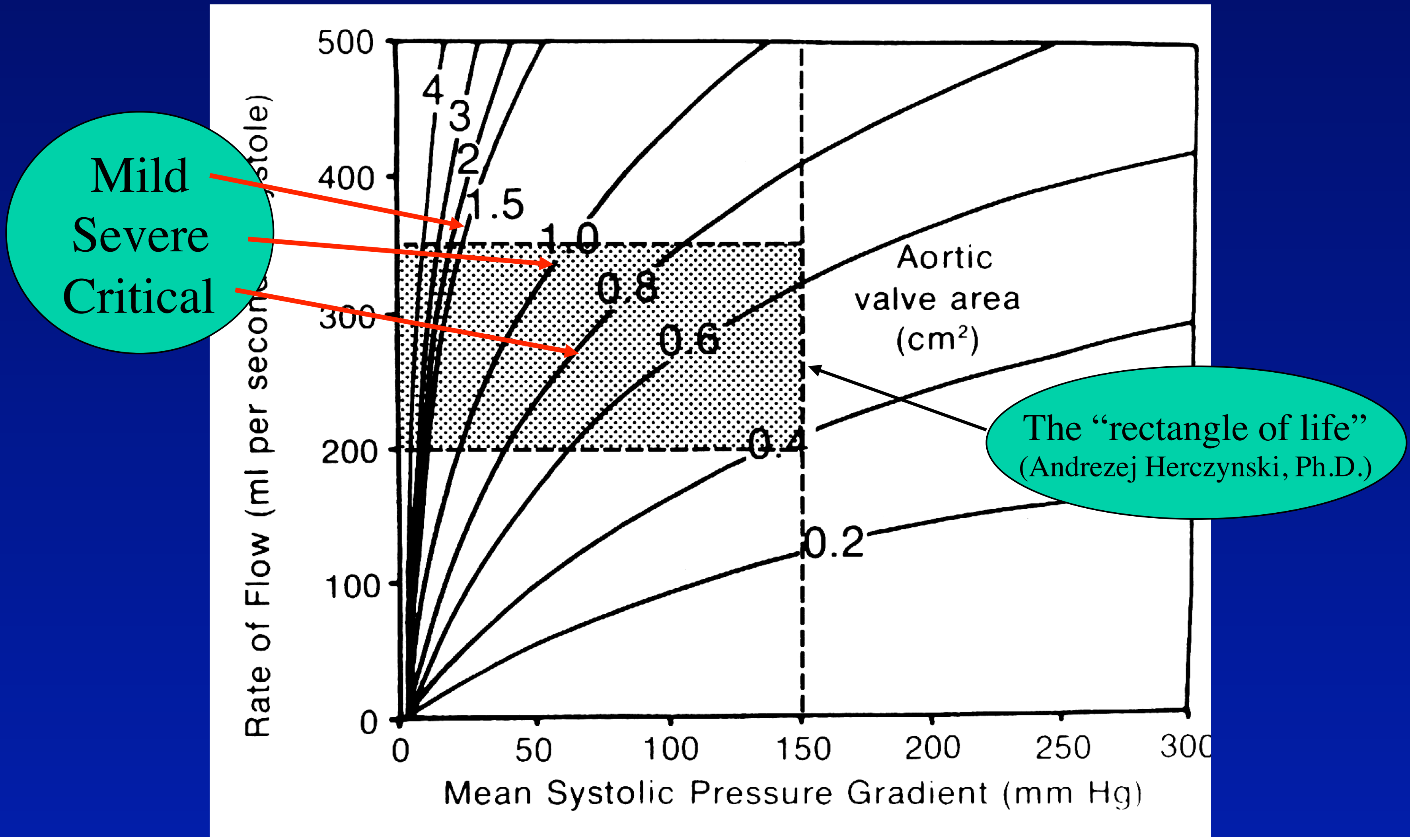
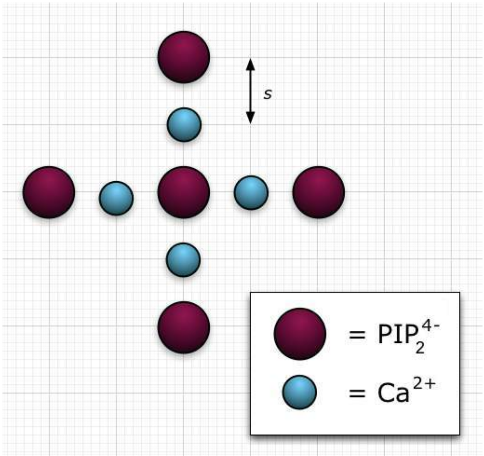
Aortic Stenosis

Relationship between Valve Orifice Area and Severity



Physics in biological context

- Highly negatively charged lipids need to cluster together on the surface of the cell membrane to accomplish certain cellular processes. For the simple model of a cluster provided, show that the electric force on the bottom lipid headgroup is attractive with Ca^{2+} ions but not with Na+ ions.



Based on work by Wang, Collins, Guo, Smith-Dupont, Gai, Svitkina, and Janmey, 2011.

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Physics in biological context

- In pure water, double-stranded DNA tends to separate into two strands, but in salt water, it stays together. Explain why in terms of the electrical interactions between the backbones.

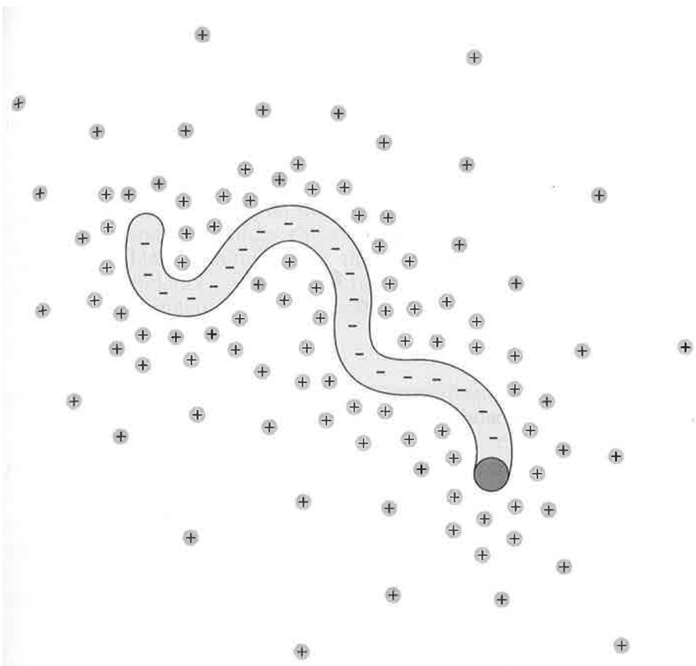

Figure 9.14 DNA in an ionic solution. The schematic shows the large negative charge density on the DNA molecule and the positive counterions in the surrounding solution.

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Physics in biological context

- What physical factors affect the speed of nerve signal propagation?

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Why develop new IPLS courses?

- Physical science content and skills increasingly important for life scientists and physicians
- Typical introductory physics not designed for life science students
  - Critically important topics glossed over/omitted
  - Formula-based exercises instead of challenging problem solving and conceptual reasoning
- Meaningful context critical to learning

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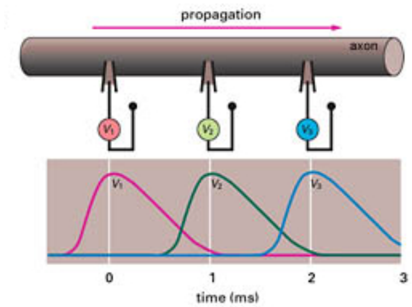
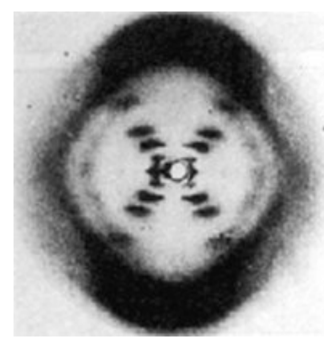
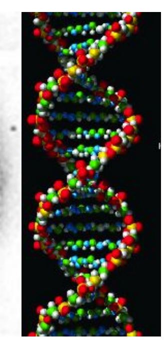
Importance: BIO 2010



- National Research Council (2003)
- Importance of physical science and quantitative methods for future life scientists
- “Connections between biology and the other scientific disciplines need to be developed and reinforced so that interdisciplinary thinking and work become second nature.”





Importance: HHMI/AAMC

- *Scientific Foundations for Future Physicians* (2009)
- Recommends competency-based (*not* course-based) requirements for medical school admissions
- Competencies include both physics content and scientific skills
- MCAT revision underway for 2014

AAMC
Tomorrow's Doctors, Tomorrow's Cures®

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Importance: Bio/med educators

- Biology faculty want this course to serve their students well!
- "Medicine is about solving high-stakes problems with incomplete and sometimes conflicting data under time pressure."
  — John Hirshfeld (University of Pennsylvania School of Medicine)

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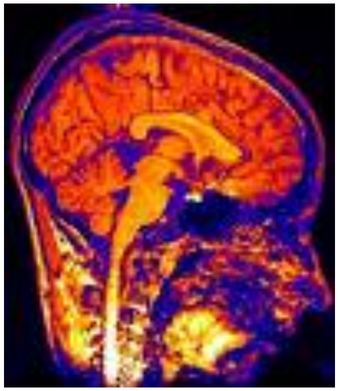
Context: critical for learning

- Motivating context ("why does this matter?") facilitates learning
  • cognitive apprenticeship



Heller & Heller, "Using the Learning Knowledge Base" (2004)
Collins, Brown, and Holum, "Cognitive Apprenticeship: Making Thinking Visible" (1991)

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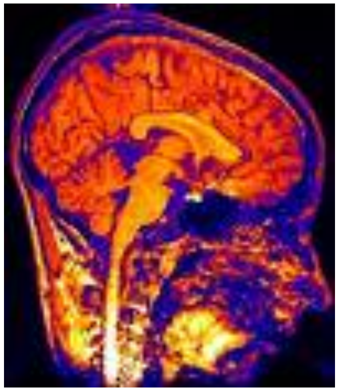
  • expansive framing



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Engle, Nguyen, and Mendelsohn, "The influence of framing on transfer" (2011)

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Expansive framing experiment

- High school biology students tutored about circulatory system
- Ability to apply (“transfer”) knowledge to describe respiratory system depends on framing provided by tutor
- Students transferred more when lesson presented as broadly relevant

Engle, Nguyen, and Mendelsohn, “The influence of framing on transfer” (2011)

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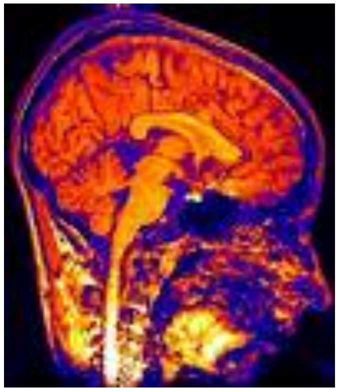

- If goal is for students apply physics to biology, teach them by doing so!

Heller & Heller, "Using the Learning Knowledge Base" (2004)
Collins, Brown, and Holum, "Cognitive Apprenticeship: Making Thinking Visible" (1991)
Engle, Nguyen, and Mendelsohn, "The influence of framing on transfer" (2011)
Redish, Teaching Physics with the Physics Suite *(2003)*
Schwartz, Bransford, & Sears, "Efficiency and Innovation in Transfer" (2004)

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Goals of an exemplary IPLS course

- Teach most appropriate physics topics with sound pedagogy
- Place physics in rich (“authentic”) biological contexts
- Develop quantitative scientific skills

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Appropriate physics topics

- Consult with life science colleagues

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Appropriate physics topics

- Consult with life science colleagues
- Build explicit connections to your institution's biology and chemistry departments

    examples

    "As you learned in …"

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Topics: what needs to be added?

- Fluid statics and dynamics
- Elastic properties of materials
- Energy: open systems, nonmechanical
- Statistical physics: diffusion, osmotic pressure, electrochemistry, free energy
- Geometric and wave optics
- Electrostatics in materials
- Circuits (neuroscience, electrophysiology)

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Topics: What gets left out?

- Significantly reduce kinematics
- 2D/3D momentum and collisions
- Angular dynamics
- Planetary orbits
- Gauss's Law
- Magnetic field calculations
- AC circuits and inductance

Hard choices have to be made!

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Sound pedagogy

Take advantage of insights from physics education community:

- Emphasize both qualitative reasoning skills and quantitative problem solving
- ConcepTests, ranking tasks, tutorials
- Context-rich problems

Adapt validated materials from “regular” physics courses whenever possible

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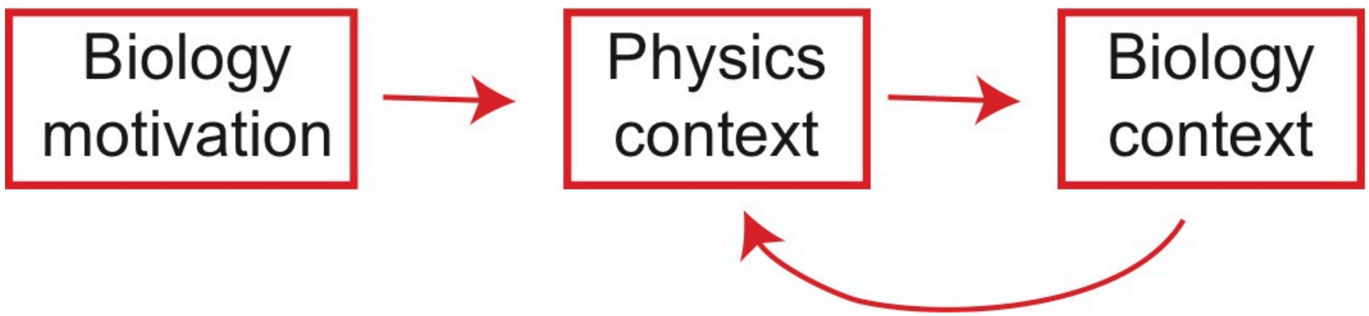
Physics in biological context



- Contexts include both biology (“macro” and “micro”) and instrumentation
- Physics must give significant insight into biology contexts
- Development requires both biology and physics teaching expertise!

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Scientific skills

HHMI Competency E1: “Apply quantitative reasoning and appropriate mathematics to describe or explain [natural phenomena].”

- “Demonstrate quantitative numeracy and facility with the language of mathematics.”
- Interpret, use, and devise mathematical models, including growth/decay with calculus
- Dimensional analysis, estimation, proportional reasoning
- Graphical analysis of quantitative data

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Scientific skills

Consider the effect of changing the various size parameters of a worm. First consider a worm of length 12 cm that grows by increasing its radius with fixed length. Use a spreadsheet to plot the total oxygen absorbed through the skin of the worm and the total oxygen used by the worm as a function of its length, from a radius of 0 cm (not really reasonable) up to a radius of 1 meter. Do the two curves cross? Explain what the crossing means and what its implications are.

--- University of Maryland NEXUS team

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Scientific skills

HHMI Competency E2: “Demonstrate understanding of the process of scientific inquiry and . . . how scientific knowledge is discovered and validated.”

- Articulate hypotheses, design experiments
- Make quantitative measurements with “basic laboratory instrumentation”
- Analyze, interpret, and present quantitative data (including errors)

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Implementation at Swarthmore

Implementation at Swarthmore

Insufficient FTEs for year-long reformed course

Need traditional course for engineers

Offerings:

- Traditional 1st semester of university physics (Phys 3)
- Traditional (Phys 4) and biological context (Phys 4L) 2nd semester

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Implementation at Swarthmore

- Three hours of Peer Instruction lecture
- Weekly 3-hour laboratory
- Adding CGPS as part of lab
- Weekly homework: qualitative reasoning, estimations, context-rich problems, and preparation for laboratory

PI: Crouch, Watkins, Fagen, and Mazur (2007).
CGPS: Heller & Heller (2004).
Redish, Teaching Physics with the Physics Suite (Wiley, 2003)

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Implementation at Swarthmore

- Modified syllabus
- Organize each topic and unit around one or two biological contexts
  - Optics: confocal microscopy and human vision
  - Electricity (including circuits): nerve signaling
  - Induction: Pacemaker safety
- Context-rich problems, models, estimation, and conceptual reasoning
- Problem-solving laboratories
- Work in progress!

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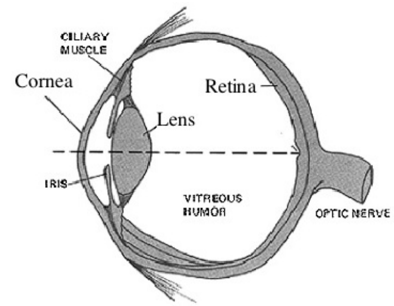
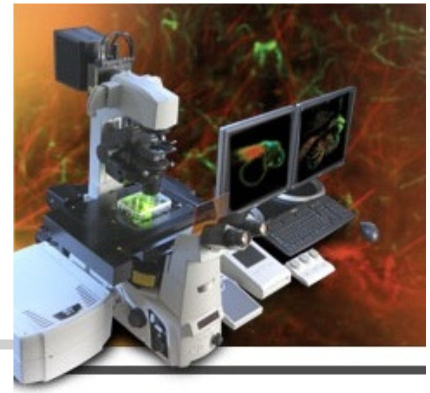
Ray optics





- Human vision: fixed retina, adjustable lens
- Usual physics: move object with fixed lens *f* → moves image

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ConcepTest: physics context

A projector uses a converging lens to form a focused image of a bright source on a screen.

If the lens is moved closer to the source, how should the screen be moved, if at all, to keep the image in focus?

1. Closer to the source
2. Farther from the source.
3. The image remains focused without moving the screen.
4. Need more information.

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ConcepTest: biological context

You are in a garden initially looking at a nearby flower. If you then turn your gaze to a tree that is farther away, how does the focal length of your eye's lens change, if at all?

1. The focal length increases.
2. The focal length decreases.
3. The focal length remains the same.
4. Need more information.

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ConcepTest: biological context

You are in a garden initially looking at a nearby flower. If you then turn your gaze to a tree that is farther away, how does the shape of your eye's lens change, if at all?

1. The lens becomes rounder (more curved).
2. The lens becomes flatter.
3. The lens shape remains the same.
4. Need more information.

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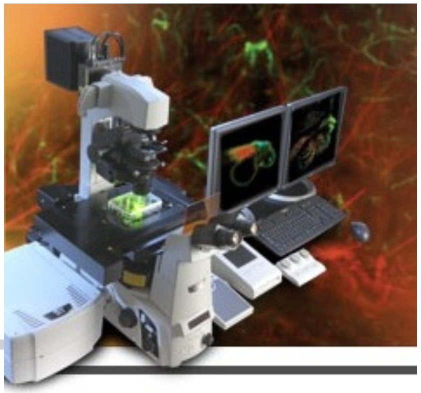
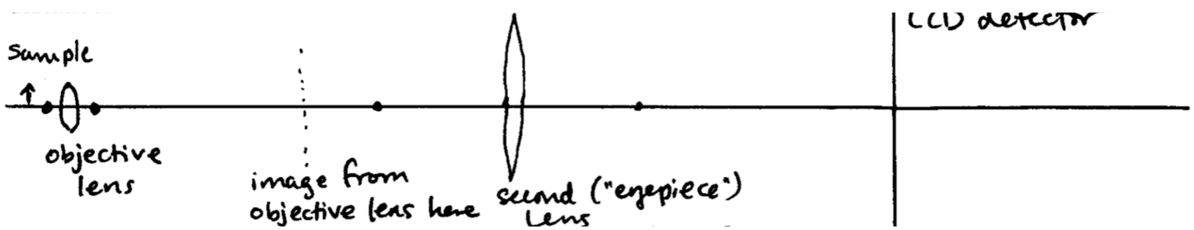
Microscopes



- Usual physics textbooks: misleading or confusing diagrams of single design of compound microscope
- Instead: teach students to analyze images formed with multiple lenses

Biological context problem

You are using a microscope that produces an image recorded by the light-sensitive detector of a CCD camera. The microscope has a 40x objective lens and a second +10 cm focal length lens giving 2x additional magnification. The figure showing the optical arrangement is **not** to scale.



(a) Is the image on the detector real or virtual? Upright or inverted (relative to the sample)?

(b) If the sample is 2.0 mm from the objective when the final image is in focus, how far is the detector from the objective lens?

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Labs: optical instruments

- Working distance of different microscope objectives
- Vision correction
- Constructing a compound microscope to produce either a real or a virtual image

All use PASCO Basic Optics kit

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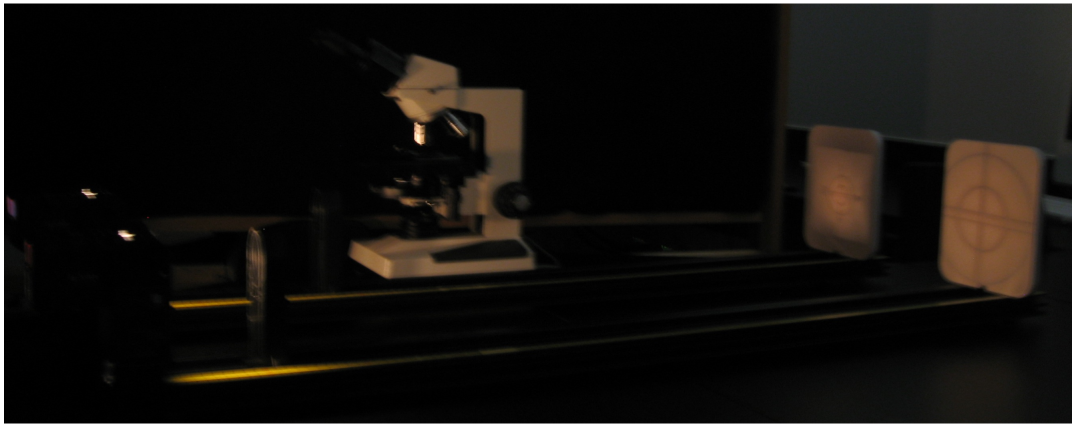
Labs: working distance

- Microscope optics: sample and image planes fixed, adjust lens position
- Lab: fixing “sample” and screen positions, compare +10 cm and +20 cm lenses. Which lens produces the bigger image? Which lens is closer to the sample?



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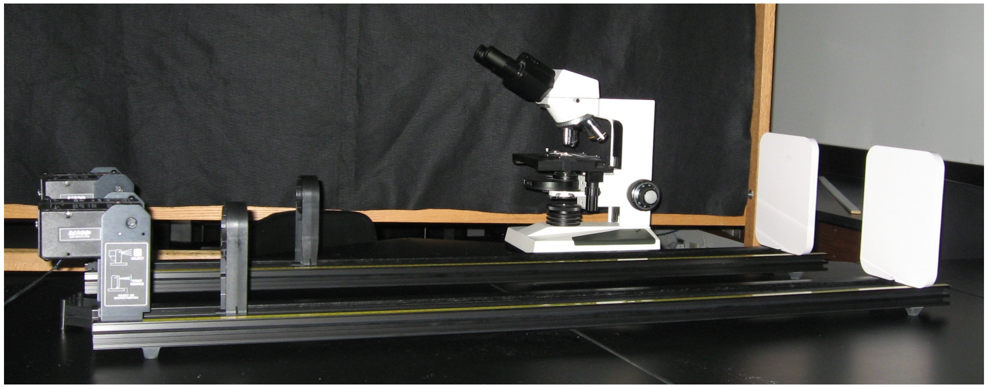

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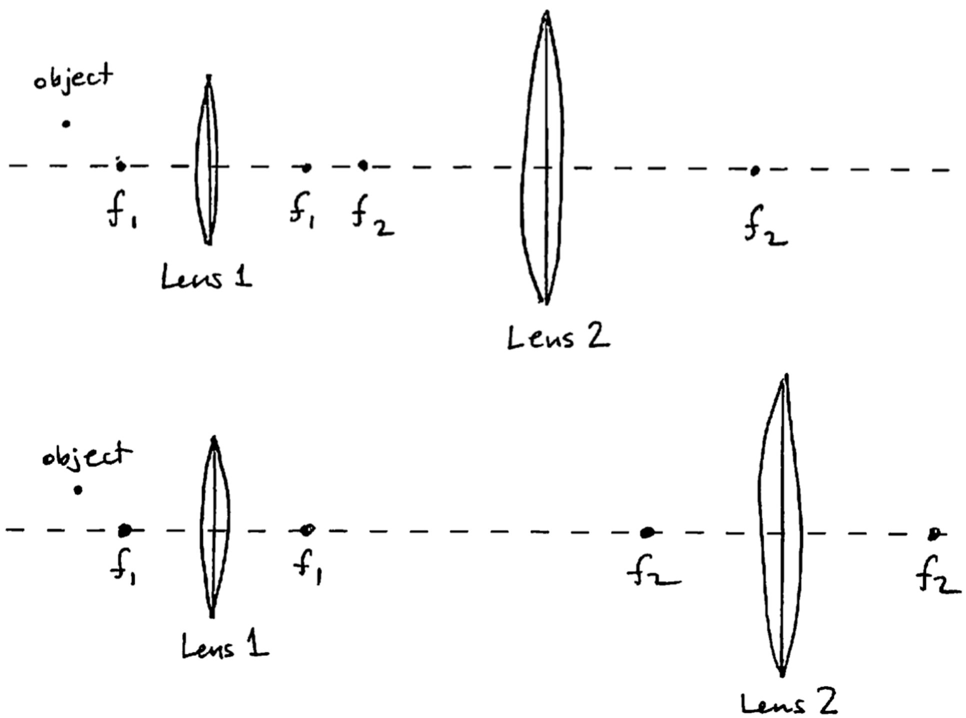
Labs: compound microscope

- Prelab scaffolding based on “Convex Lenses” Tutorial (UW-PEG)



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Labs: compound microscope

- Construct models of two types of compound microscope on the optical track:
  (i) the image is viewed by the scientist looking through the eyepiece lens
  (ii) the image is “captured” on a screen (representing a CCD detector)

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Labs: vision correction

- Construct model of a nearsighted eye: image of nearby source is focused, image of distant source is blurry
- Provide corrective lens to produce focused image of distant source
- Calculate corrective lens focal length from measurements

Optics capstone: confocal microscopy

Obtain three-dimensional images of biological samples with diffraction-limited (~200-nm) resolution

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Optics capstone: confocal microscopy

Combines ray optics with limits of resolution

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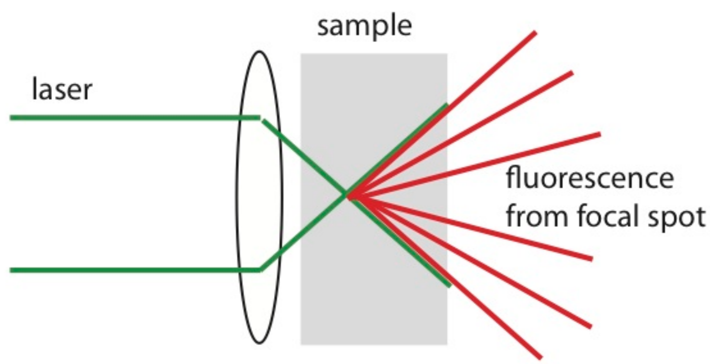
Confocal microscopy

- Ray optics: imaging with converging lenses
- Wave optics: diffraction limit
- 3D images: a stack of planar images
- Planar images obtained pixel by pixel



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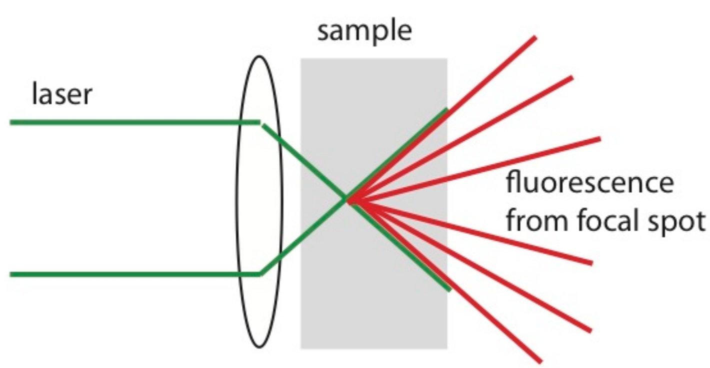

What about fluorescence outside the focus?

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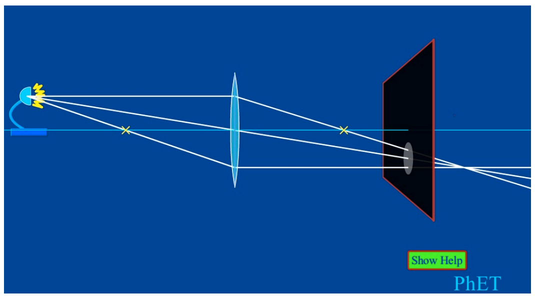
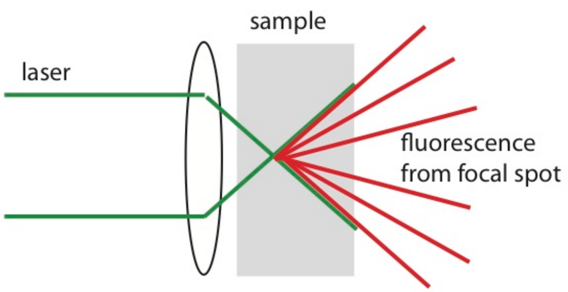
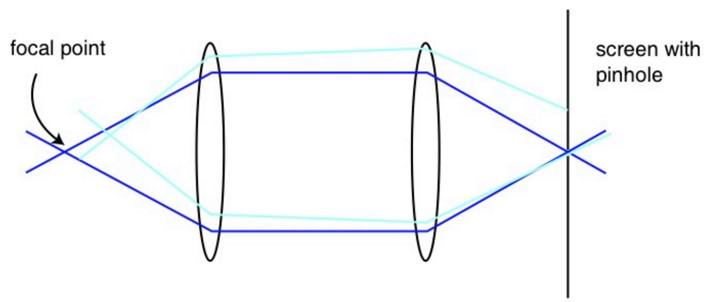
Confocal microscopy

Depth of focus (qualitatively)



Pinhole blocks out-of-plane fluorescence!





Semwogerere & Weeks, 2005

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How does the course work?

Outcomes: enrollment

- 2008: 43 in Phys 4L, 20 in Phys 4
- 2010: 60 in Phys 4L, 27 in Phys 4

    15 students waited to take Phys 4L instead of Phys 4
- 2012: 75 in Phys 4L, 32 in Phys 4

    24 students waited

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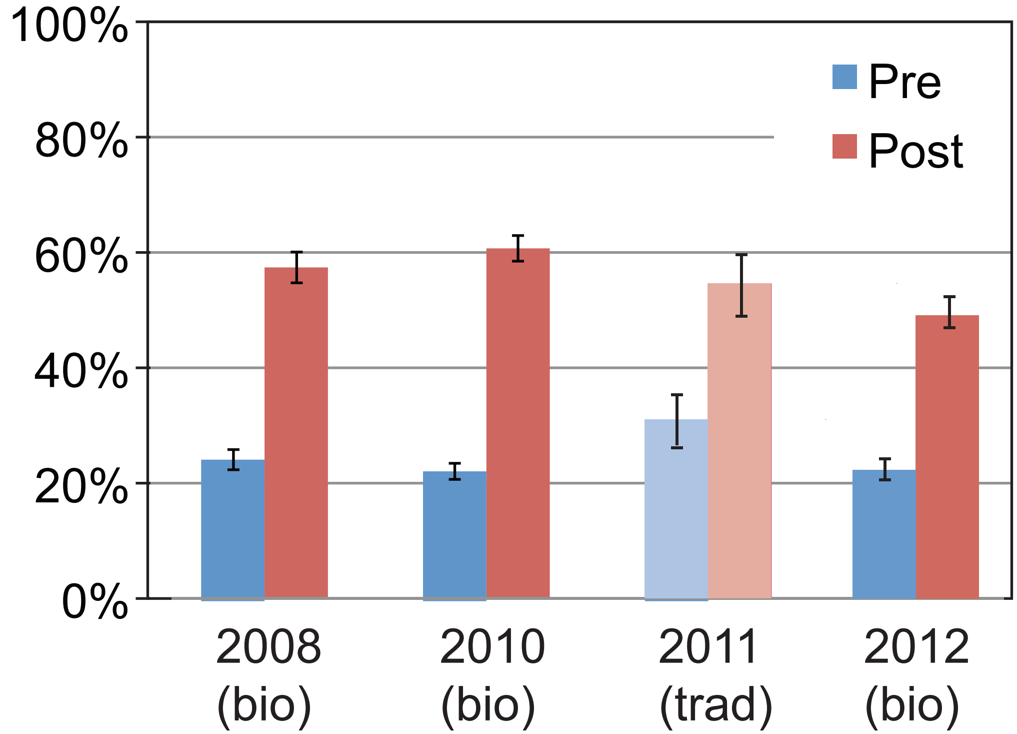
Outcomes: BEMA



- Similar or better scores to traditional second semester course

Outcomes: student attitudes

- Very positive course evaluations
- 63% mention life science applications as highlight
- CLASS study underway at Swarthmore

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2012 course evaluation

At the beginning of this course, I expected physics to be:

Response	Average	Total
very useful in understanding the life sciences	21%	14
somewhat useful in understanding the life sciences	57%	38
of little use in understanding the life science	24%	16

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2012 course evaluation

Now at the end of this course, I consider physics to be:

Response	Average	Total
very useful in understanding the life sciences	55%	37
somewhat useful in understanding	43%	29
of little use in understanding the life science	1%	1
of no use in understanding the life sciences	1%	1

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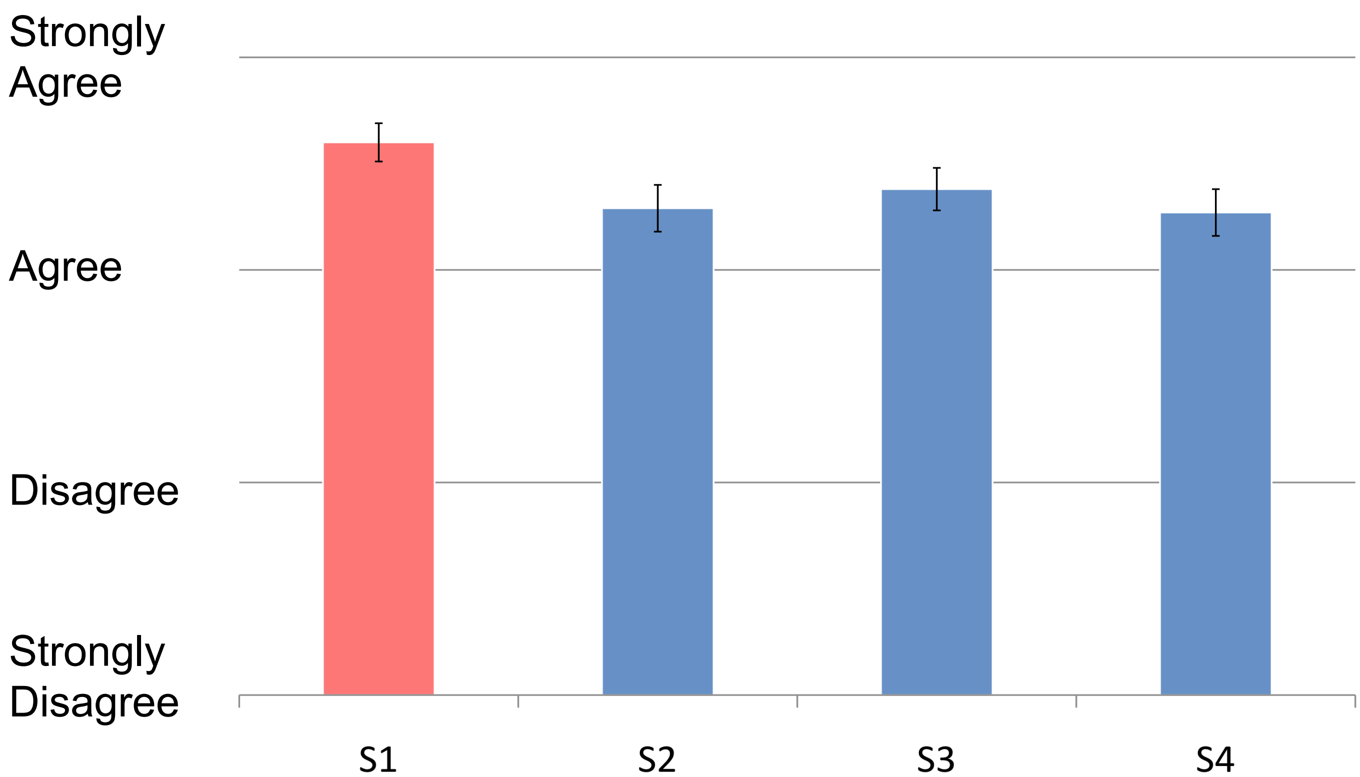
2010 HHMI evaluation

"Including biological examples helped me enjoy physics more than if we had used non-biological examples."



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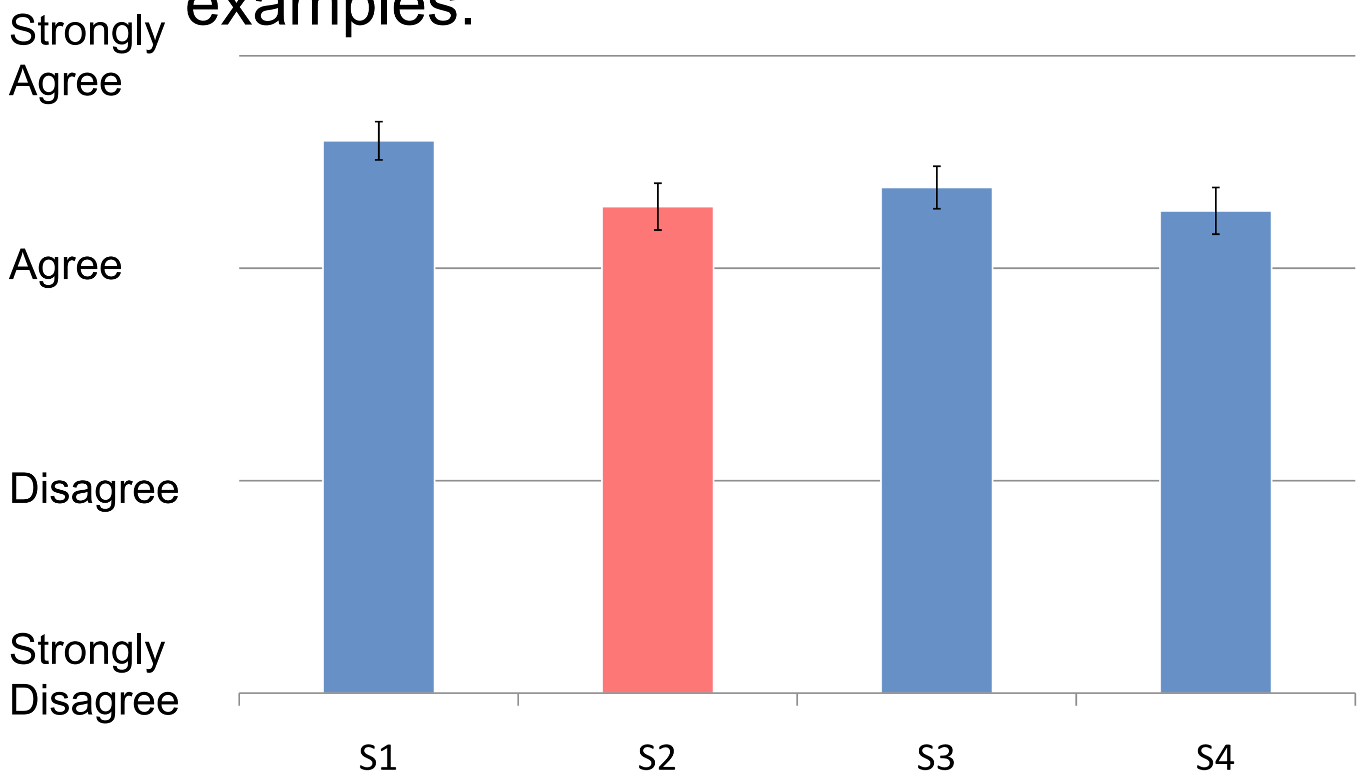

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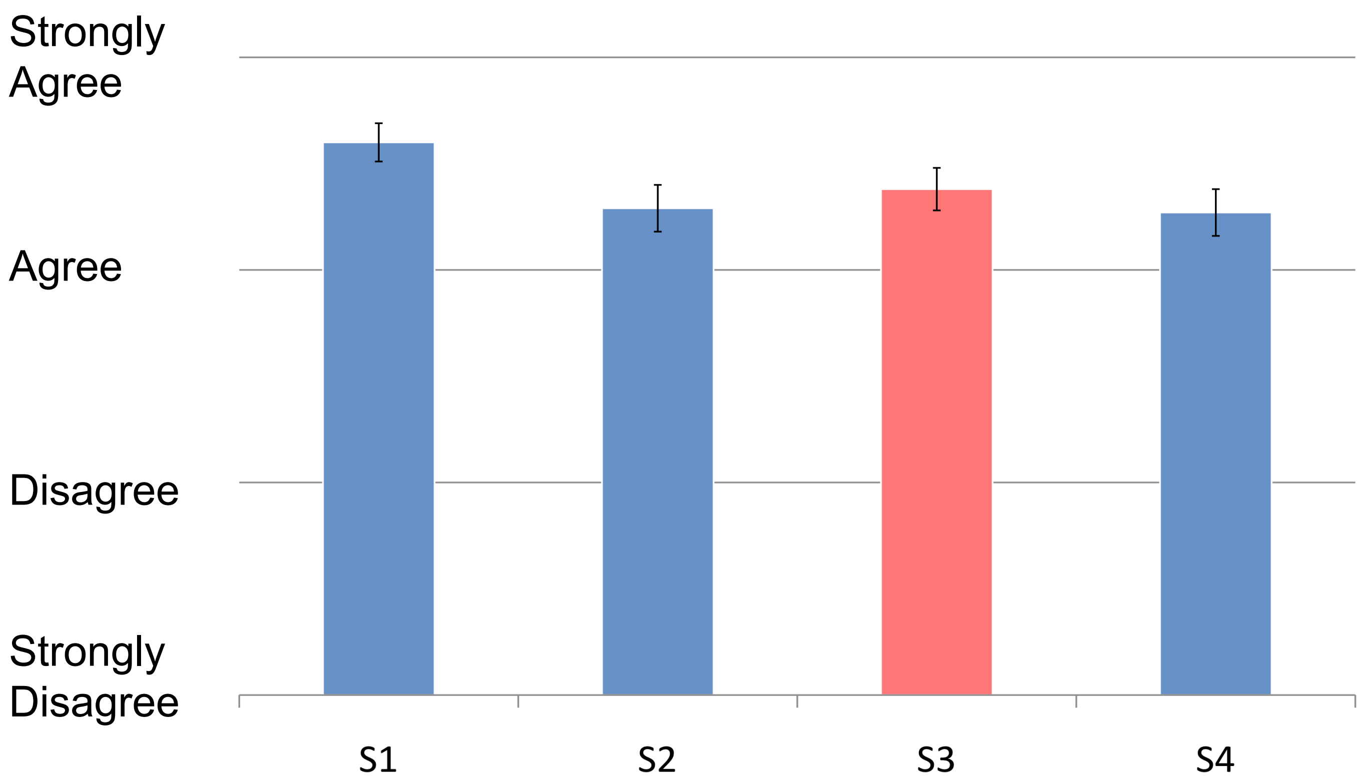
2010 HHMI evaluation

"This course helped me think about biology in useful new ways."



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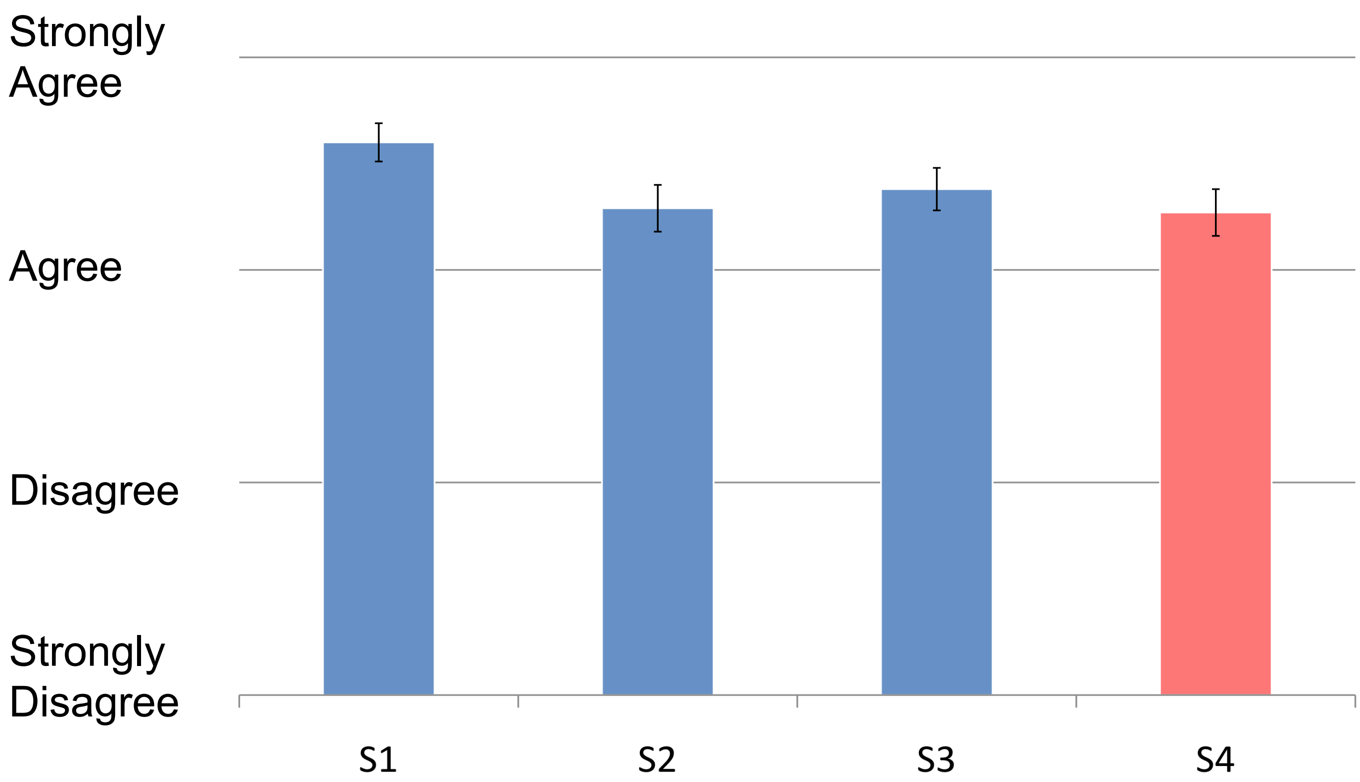
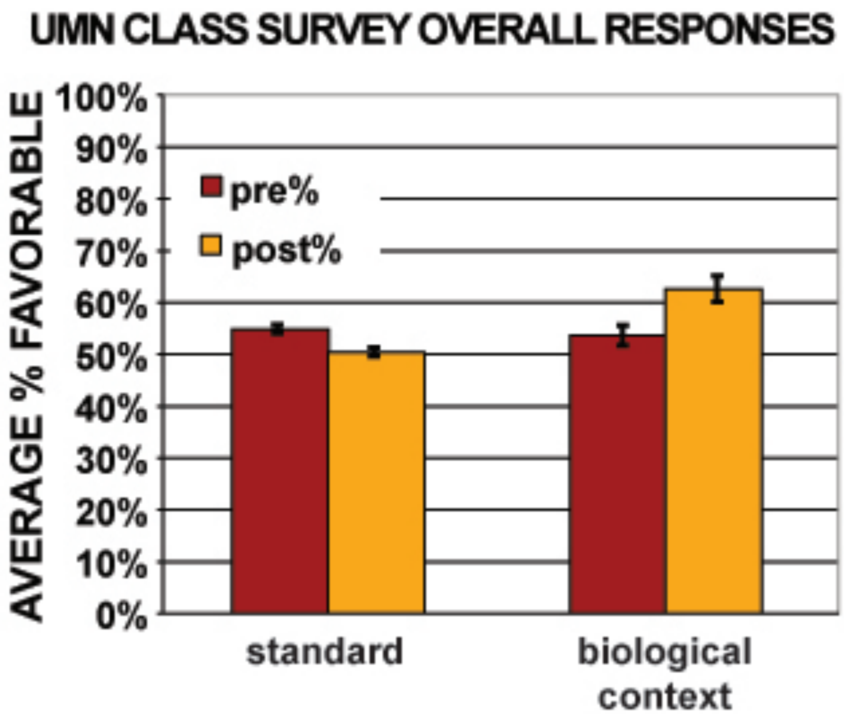
2010 HHMI evaluation

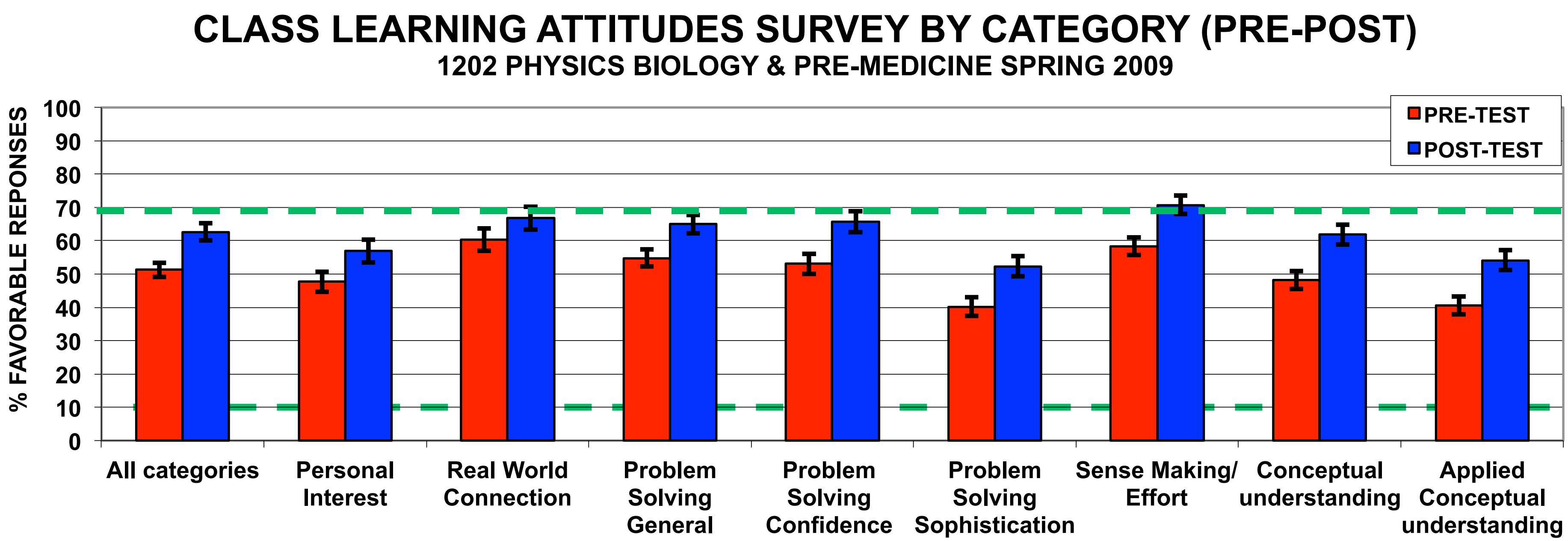
"Methods I learned in physics will be useful for me in my future career."



Outcomes: Minnesota CLASS



Outcomes: Minnesota CLASS



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Course evaluation comments

- "I often found myself thinking, 'Oh, so that's how it works,' because I'd never really thought about the physics behind some of the biological concepts I'm very familiar with." (Junior biology major)
- "I liked having a physics class that was geared toward including some biology…[In the past] I didn't see the direct connections with the real world and how I could apply physics. This class has helped me see just that." (Junior biology major)
- "The applications to biology that were covered only in class (not in the book) were the most interesting part of the class." (Sophomore chemistry major)

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Email from student

- “I wanted to tell you how well Physics 4L prepared me for my summer …. All of the [work] we did modeling the cell membrane as a capacitor and the discussions we had about neurons as parallel circuits really prepped me for the more complicated things I have been doing here. Recently I’ve been calculating currents through membrane potassium and sodium channels and accounting for leakage.” (Junior biology major)

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Resources

- Many similar courses launching nationwide
- Regular AAPT meeting sessions since 2009 (Juan Burciaga)
- GWU workshop October 2009 (Mark Reeves, Bob Hilborn) http://www.gwu.edu/~ipls/
- Physics and Biology Gordon Conference 2014

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Thanks to …

- HHMI and Mellon grants to Swarthmore
- Many colleagues at Swarthmore and elsewhere
- Tim McKay, Suzanne Amador Kane, Mark Reeves, and Bob Hilborn (co-organizers of GWU workshop)
- Joe Redish, Ken Heller

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