Teaching Introductory Physics in Biological Context

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Today's talk

- Why develop new introductory physics for life sciences (IPLS) courses?
- Features of an exemplary IPLS course
- Implementation at Swarthmore
- Future directions

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Why develop new IPLS courses?

- Physical science content and skills increasingly important for life scientists and physicians
- Typical college 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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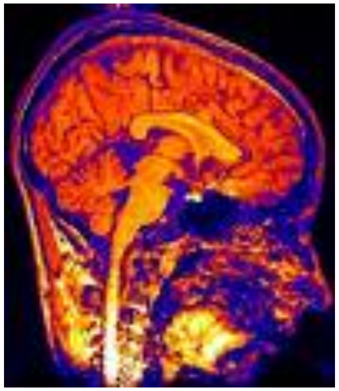
Context: critical for learning



- Motivating context ("why does this matter?") facilitates learning
- New knowledge must connect to existing knowledge
- Providing biology connections now may help students apply physics to biology later

Heller & Heller, "Using the Learning Knowledge Base" (Project Kaleidoscope, 2004)
Redish, Teaching Physics with the Physics Suite (Wiley, 2003)
Schwartz, Bransford, & Sears, "Efficiency and Innovation in Transfer" (Information Age Press, 2004)
Zull, The Art of Changing the Brain (Stylus Publishing, 2002)

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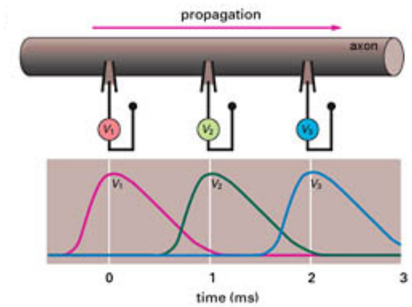
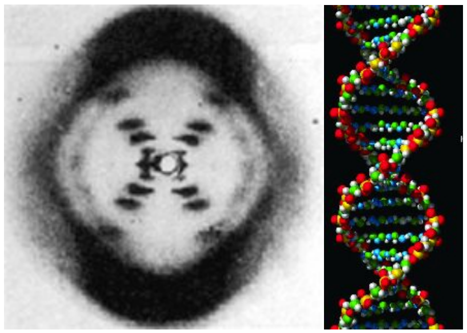
Importance: BIO 2010



- 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) premedical admissions requirements
- Competencies include both physics content and scientific skills
- MCAT revision underway for 2014

Importance: Life science/ medical educators

- Biology faculty welcome dialogue about this course!
- Physical sciences undergird both living systems and critical technology
- “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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Exemplary IPLS course

- Pedagogically sound
- Most appropriate physics topics
- Place physics in rich biological contexts
- Develop scientific skills

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Topics to expand or refocus

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

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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

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

- 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 (need improvement!)

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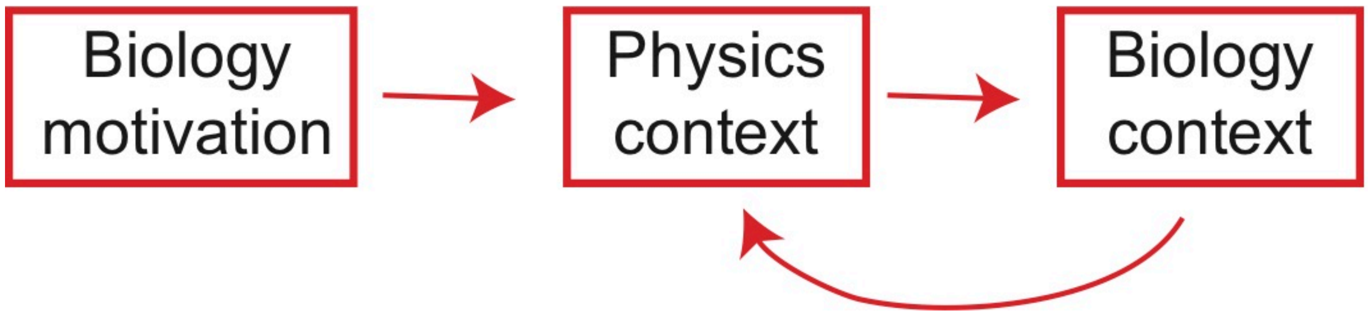
Physics in biological context



- Contexts include both biology (“macro” and “micro”) and instrumentation
- Physics must give significant insight into biology contexts

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Implementation at Swarthmore

- Three hours of Peer Instruction lecture
- Weekly 3-hour laboratory
- Informal, optional problem solving sessions with peer tutors (considering CGPS)
- Weekly homework: qualitative reasoning, estimations, context-rich problems (both physics and biological contexts), 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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Peer Instruction

- Lectures interspersed with conceptual questions
- All students given time to think, respond, and discuss
- Students gain conceptual understanding
- Quantitative problem solving remains strong

Crouch and Mazur, *Am. J. Phys.* **69** (9), 970 (2001).

Crouch, Watkins, Fagen, and Mazur, in *Research-based Reforms of Introductory Physics* (AAPT, 2007).

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Cooperative group problem solving

- Students instructed in expert problem solving strategy
- Students work in groups of three on challenging problems
- Problems require multiple steps, often involve estimation or obtaining other information

Kenneth Heller & Patricia Heller, *"Using the Learning Knowledge Base" (Project Kaleidoscope, 2004),* and other publications of the University of Minnesota Physics Education Group.

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Implementation at Swarthmore

Insufficient FTEs for year-long reformed course

- Traditional 1st semester of university physics (Phys 3) offered yearly
- Traditional 2nd semester (Phys 4) offered yearly
- Biological context 2nd semester (Phys 4L) offered in even years

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Second semester syllabus

- Removed: 3 weeks of traditional E&M
  Gauss's and Ampere's Laws
  AC circuits
  Maxwell's equations
- Added:
  1.5 weeks of optics
  1.5 weeks of E&M contexts
- Includes 2 classes on electrostatics in dielectrics

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Optics capstone: confocal microscopy

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

Optics capstone: confocal microscopy

Understanding combines ray and diffractive optics!

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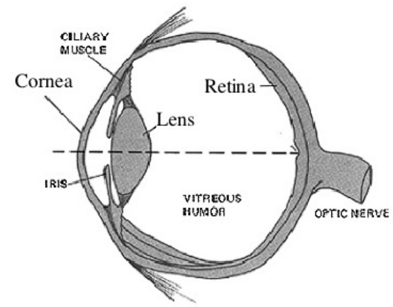
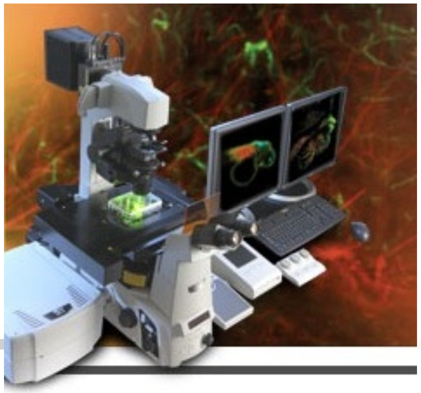
Ray optics





Sequence:

- Light travels in straight lines (rays)
- Pinhole images (invertebrate vision)
- Light and materials: reflection and refraction
- Images in plane mirrors (virtual images)
- Total internal reflection (optical fibers)
- Focusing with converging lenses
- Real images with single converging lenses

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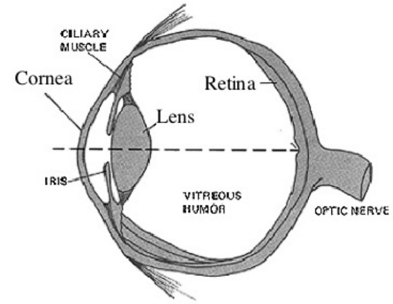
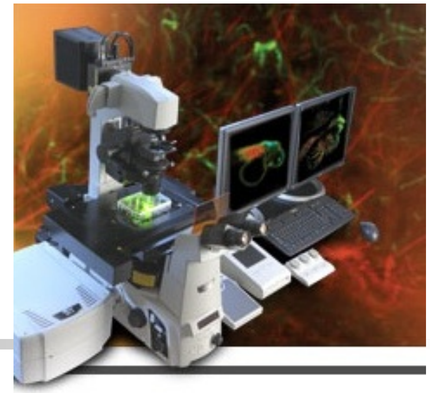
Ray optics

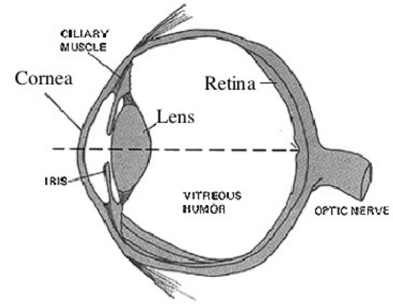


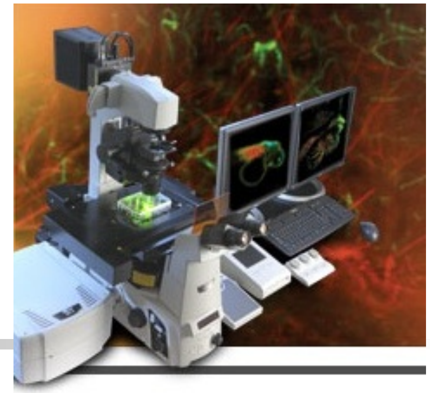


Sequence cont'd:

- Converging lens shape and focal length
- Human vision (fixed retina, adjustable lens)
- Virtual images with lenses; diverging lenses
- Image formation with two or more lenses (vision correction, optical instruments)
- (If time) Image formation with curved mirrors

Ray optics





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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.

SWARTHMORE

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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Vision deficits and correction

Nearsightedness (myopia):

Mismatch between retina location and range of lens focal lengths

Lens focal range corresponds to nearer distances

Corrective lenses form images of distant objects within eye's focal range

Biological context problem

Without glasses, your Physics 4L Science Associate, Erik, cannot see objects clearly if they are more than 80 cm from his face. Prescribe corrective lenses that will allow him to see distant objects clearly.

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Physics context problem

You hold a 10 cm focal length lens 12 cm from your page of Physics 4L notes and look through it. (Try it!) If your face is 20 cm from the lens (with the lens between your notes and your face), and you have normal (or corrected) vision, explain why you can't see anything through the lens.

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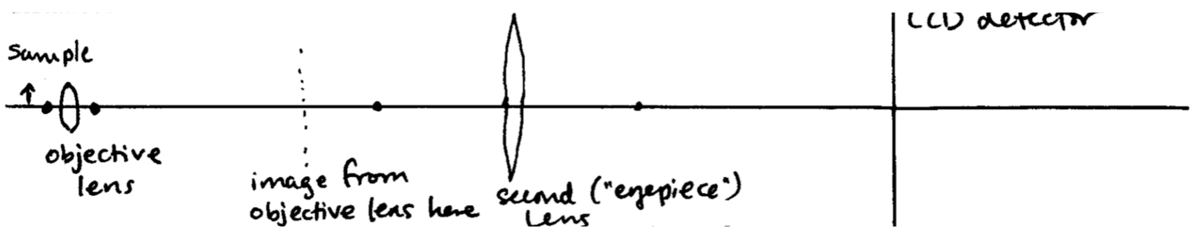
Biological context problem

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?

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

Need to increase design aspects of labs!

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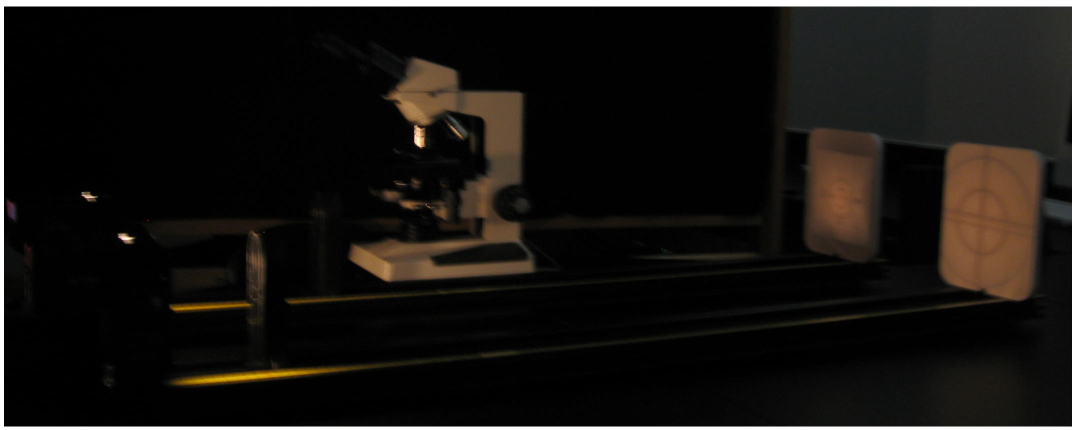
Labs: working distance

- 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?



SWARTHMORE

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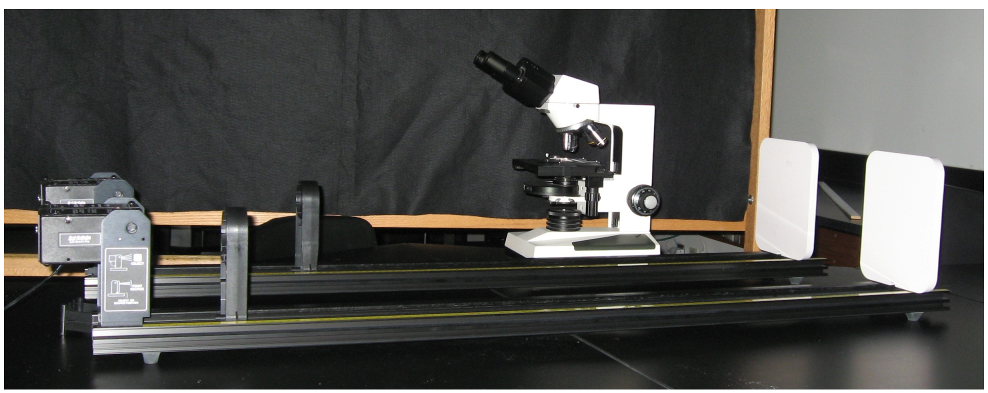

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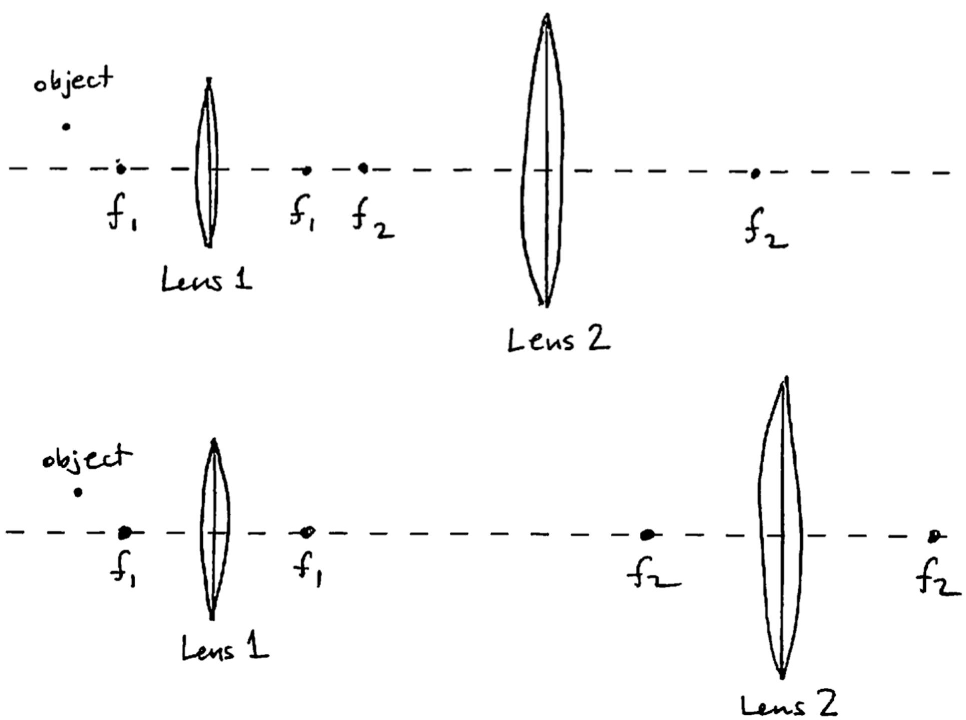
Labs: compound microscope

- 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

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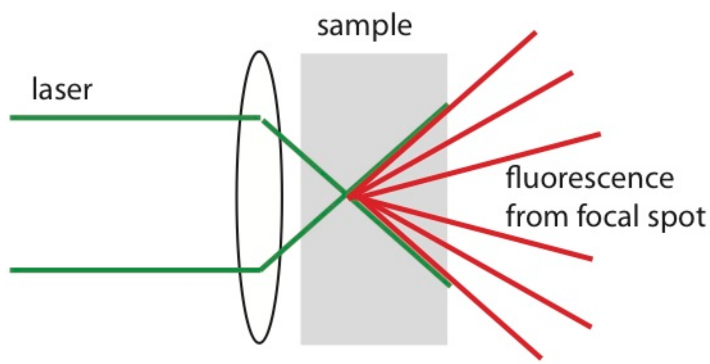
Confocal microscopy

- 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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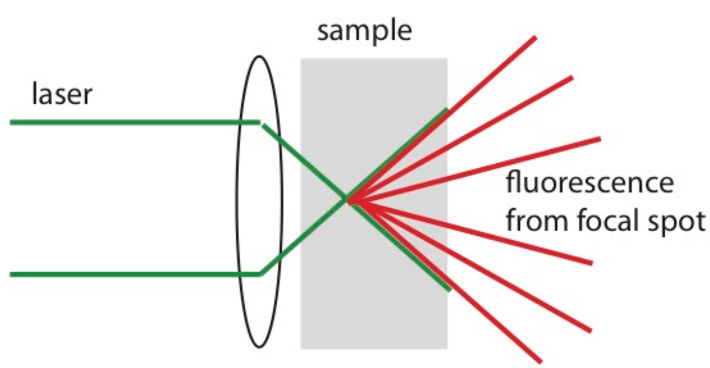

What about fluorescence outside the focus?

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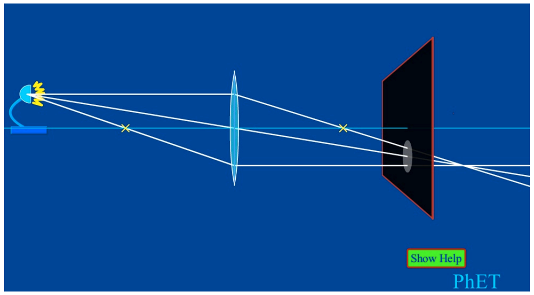
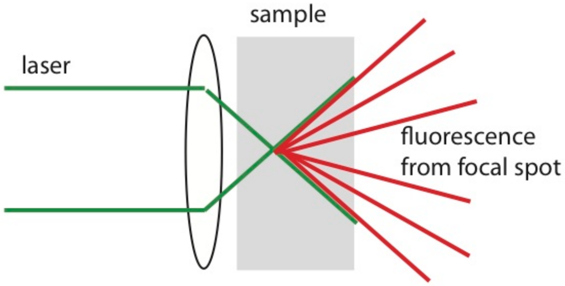
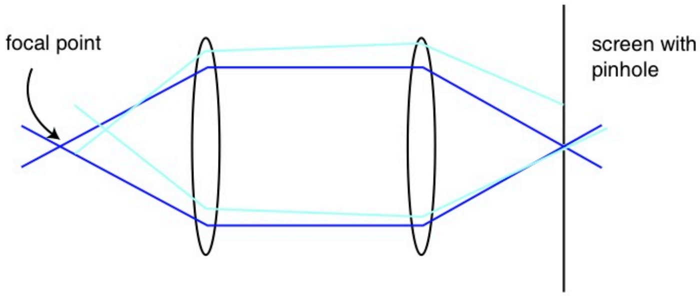
Confocal microscopy

Depth of focus (qualitatively)



Pinhole blocks out-of-plane fluorescence!





Semwogerere & Weeks, 2005

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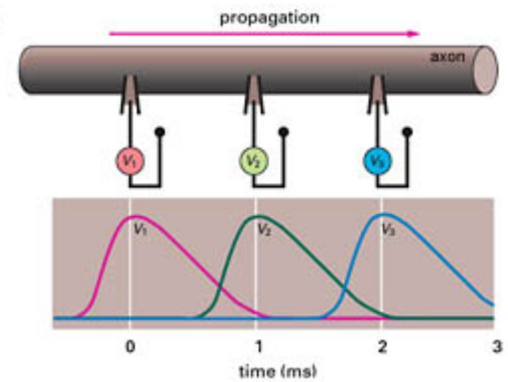

Other contexts

- Circuits: neurological action potentials, gel electrophoresis, electrocardiography
- Chemical shifts in NMR

- Magnetic sensing in bacteria and navigation in birds
- Dielectric solvent in biochemistry (reaction rates)

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How does it work?

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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 in 2010 (instead of Phys 4 in 2009)
- 2012: 68 non-first-year students preregistered for 1st semester physics

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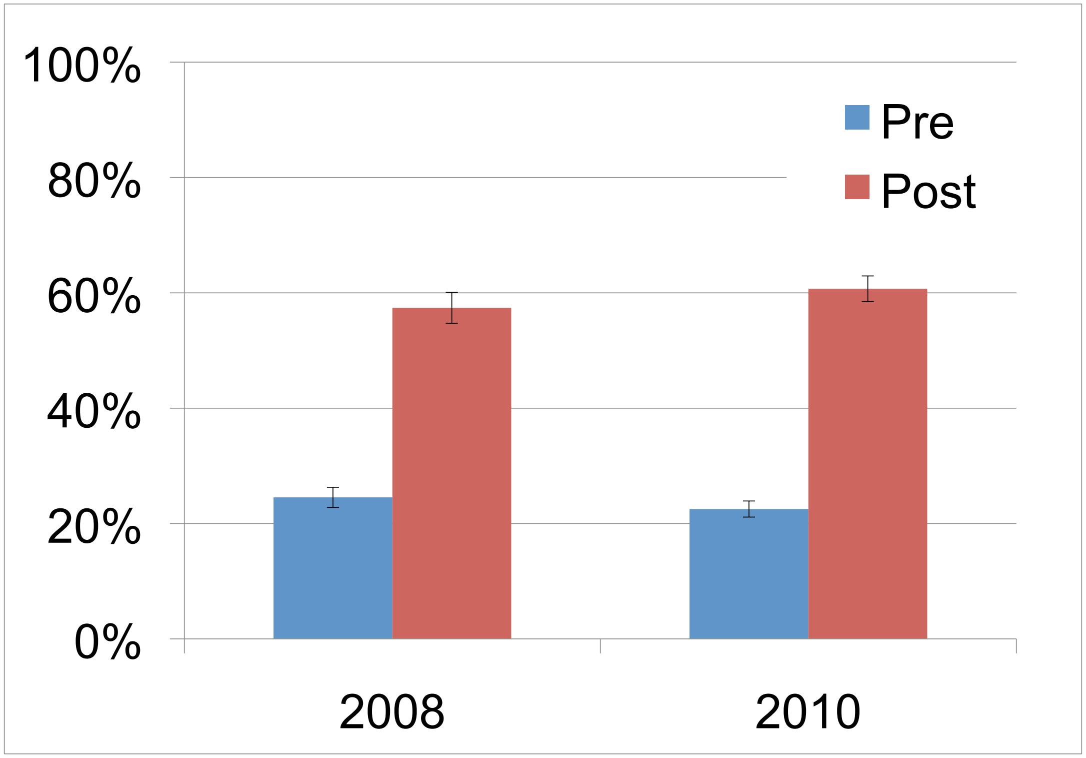
Outcomes: BEMA



- Similar scores to University of Colorado intro course for physics & engineering majors

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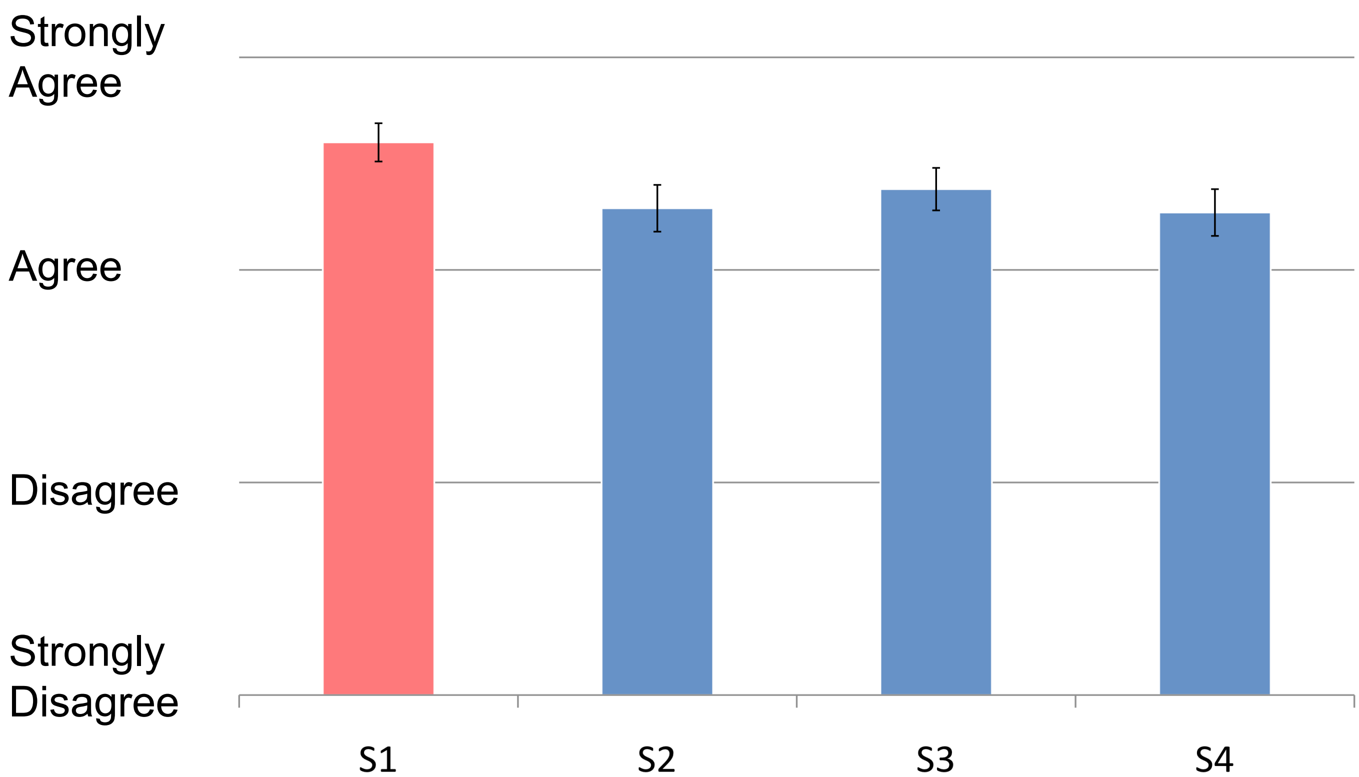
Outcomes: evaluations

- Very positive course evaluations
- 63% mention life science applications as highlight
- CLASS study underway
- HHMI evaluation (Philip Kudish, Swarthmore biology)

HHMI evaluation

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



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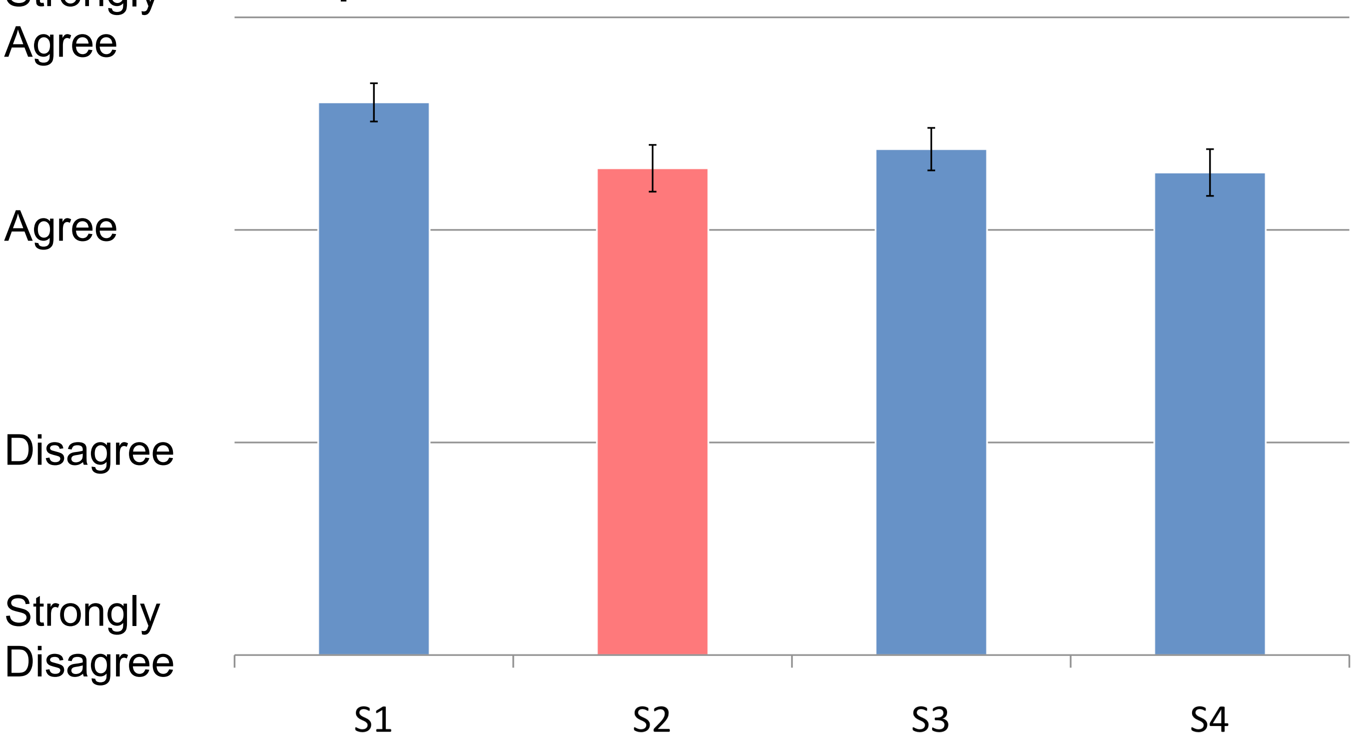
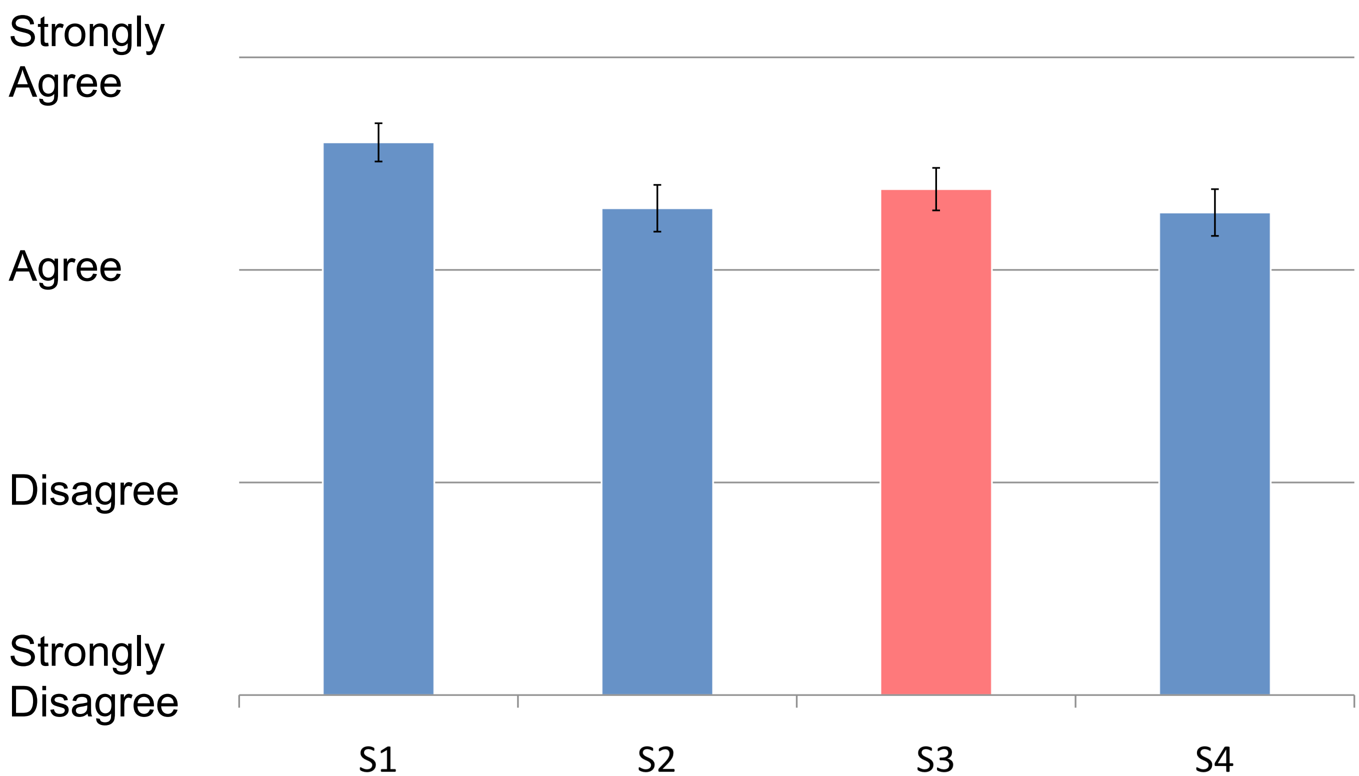
HHMI evaluation

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



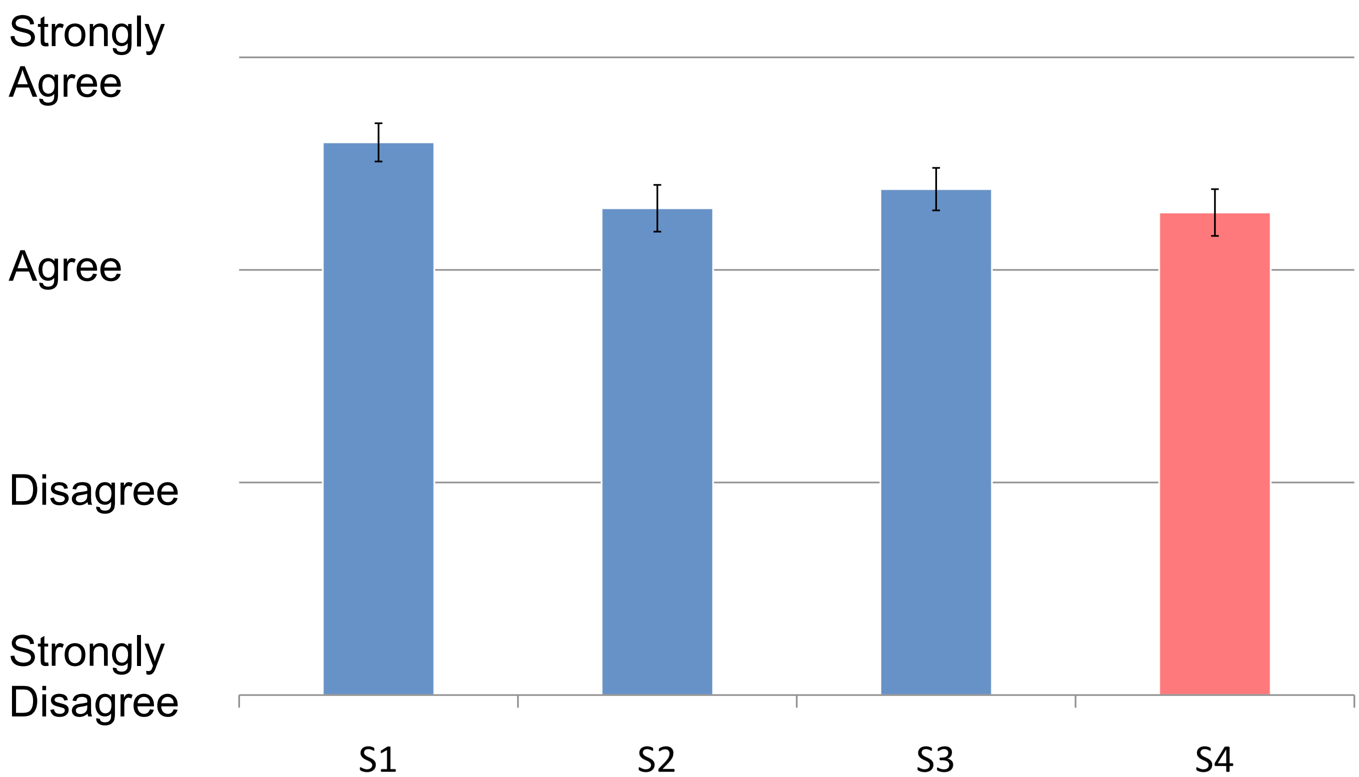
HHMI evaluation

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



HHMI evaluation

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



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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Future development

- Laboratory: biological contexts, more experimental design and hypothesis testing
- Problems, especially with model-building
- Nuclear physics and radiation

Etkina & van Heuvelen, “Investigative Science Learning Environment: A Science Process Approach to Learning Physics” (AAPT, 2007, available through COMPADRE).

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Future assessment

- Improve materials
- Motivational nature of biological contexts
- Ability of students to later apply physics to biology

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Resources

- Many similar courses launching nationwide (including here at UMBC!)
- Regular AAPT meeting sessions since 2009 (Juan Burciaga)
- GWU workshop October 2009 (Mark Reeves, Bob Hilborn)

http://www.gwu.edu/~ipls/

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Thanks to …

- HHMI and Mellon grants to Swarthmore
- Many colleagues in biology and biochemistry
- Peter Collings and Amy Cheng Vollmer (co-organizers of Mellon symposium)
- Tim McKay, Suzanne Amador Kane, Mark Reeves, and Bob Hilborn (co-organizers of GWU workshop)
- Joe Redish, Ken Heller

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Development process

- Planning with Swarthmore biology and biochemistry faculty 2005-06
- Gordon Conference June 2006
- Mellon-funded symposium at Swarthmore spring 2007
- HHMI-funded course release fall 2007: develop examples, problems, and labs
- Real-time consultation with colleagues throughout the course!

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Example: confocal microscopy

Outcomes: HHMI evaluation

- "Including biological examples helped me enjoy physics more than if we had used non-biological examples." (3.60 ± 0.09)
- "Including biological examples helped me understand physics more than if we had used non-biological examples." (3.29 ± 0.11)
- "This course helped me think about biology in useful new ways." (3.38 ± 0.10)
- "Methods I learned in physics will be useful for me in my future career." (3.27 ± 0.11)

1 = strongly disagree to 4 = strongly agree (avg ± SE) (*N* = 52); evaluation designed by P. Kudish and given as part of course evaluation

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Topics

HHMI Competency E3: “Demonstrate knowledge of basic physical principles and their application to the understanding of living systems.”

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