# Leveraging interdisciplinary connections and framing to boost interest in physics for life science students

CATHERINE H. CROUCH,
SWARTHMORE COLLEGE PHYSICS

11 APRIL 2023

# Physics education research

Add to basic knowledge about how students learn

Improve curricula and teaching methods

*Key challenges in teaching physics for life science students:*

Many students aren't interested

Many students are intimidated

Most students don't think the course is genuinely valuable for their goals — just a hurdle

*Swarthmore physics for life sciences*

*(began in 1988)*

1. *Course design*
2. *Course outcomes*

Students aren't interested in the material

Students are intimidated by the material

Students expect the course is a hurdle, not genuinely valuable for their goals

*Motivation literature:*

Interest in and value for the material supports learning

*Hidi and Renninger,* Ed. Psych. 41, *111 (2006).*
*Ainley and Patrick,* Ed. Psych. Rev. 18, *267 (2006).*
*Sansone, in* Psychology of Self-Regulation, *35-51 (2009).*
*Eccles and Wigfield,* Contemp. Ed. Psych. 61, *101859 (2020).*

# Relevance intervention

Randomized, blinded, and controlled intervention experiment ($N$ = 262):

9th grade students assigned to reflect on utility and relevance of science class material *to them*

*Hulleman and Haraciewicz,* Science 326, *1410 (2009).*

# Relevance intervention

Randomized, blinded, and controlled intervention experiment ($N = 262$):

9th grade students assigned to reflect on utility and relevance of science class material *to them*

*for students with low initial expectations of success,*
*both self-reported interest and course grades increased*

*Hulleman and Haraciewicz,* Science **326**, *1410 (2009).*

1. *Course design*
2. *Course outcomes*

## Backwards design process

Begin with desired outcomes:

- Students develop knowledge and skills valuable for their chosen fields
- Students recognize that value
- Students feel valued and respected as learners

https://tll.mit.edu/teaching-resources/course-design/backward-design/

# Backwards design process

Begin with desired outcomes:

- Students develop knowledge and skills valuable for their chosen fields
- Students recognize that value
- Students feel valued and respected as learners

# IPLS course design

Combine:

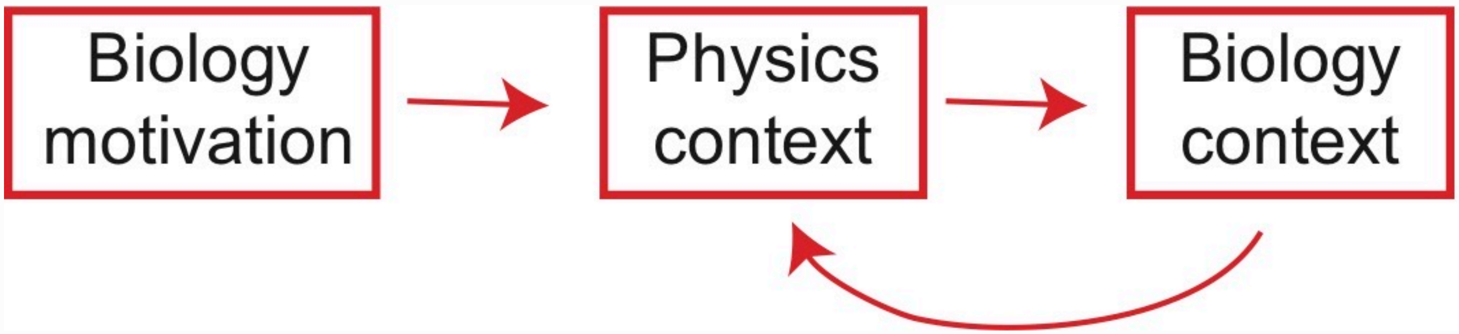
Wealth of knowledge about how to teach physics

Understanding how life scientists and medical professionals encounter and use physics

Make "authentic" connections to biology

*Watkins, Hall, Coffey, Cooke, and Redish, PRST-PER 2011.*

# IPLS course design



# IPLS course design

Centralize using physics to understand biology

Select physics content that is most important for life sciences (keeping physics story line)

*Scientific Foundations for Future Physicians*, HHMI/AAMC (2009)

*Vision & Change*, AAAS (2011)

# Professional society recommendations


*BIO 2010,* NRC (2003)
*Scientific Foundations for Future Physicians* (2009), HHMI/AAMC
*Vision & Change,* AAAS (2011)
MCAT$^{2015}$ (2013)

# IPLS course design: 1st semester

Organize each unit around authentic contexts

- Kinematics: *animal locomotion*
- Random walks/collisions: *diffusion and transport, ideal gas law, osmotic pressure*
- Forces and equilibrium: *biomechanics, spring model of DNA*
- Energy: *molecular bonds (ATP as "energy currency)*
- Thermodynamics: *thermoregulation; microscopic mechanisms*
- Fluid statics and dynamics: *circulatory systems*

# IPLS course design: $2^{nd}$ semester

Organize each unit around authentic contexts

- Optics: *animal vision, microscopy*
- Waves: *echolocation*
- Electricity/circuits: *cell membrane potential, nerve signaling*
- Magnetism and induction: *magnetic sensing, NMR*

# IPLS course design: 2$^{nd}$ semester

Organize each unit around authentic contexts

- Optics: *animal vision, microscopy*
- Waves: *echolocation*
- Electricity/circuits: *cell membrane potential, nerve signaling*
- Magnetism and induction: *magnetic sensing, NMR*

(induction stays in for "cultural" reasons)

# IPLS course design

Centralize using physics to understand biology

Most important physics content

Develop “physics toolkit”: modeling, qualitative and quantitative reasoning, multiple representations, working with data

*Build course around authentic connections*

# Authentic life science connections

Physics contributes understanding that is meaningful to life scientists

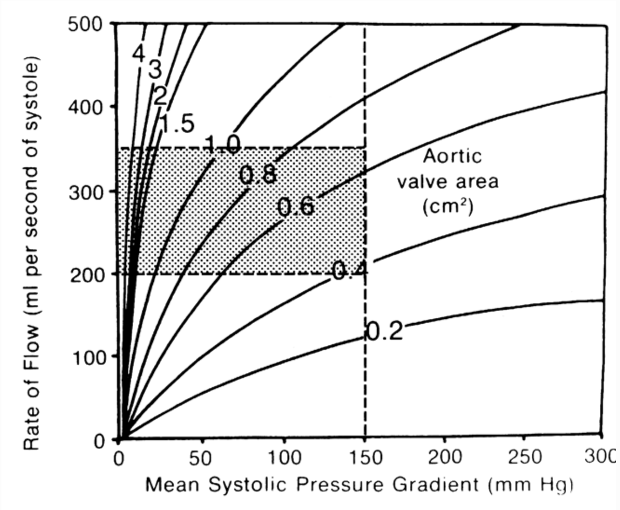
*Watkins et al., Phys. Rev. PER (2011)*

# Authentic life science connections

Physics contributes understanding that is meaningful to life scientists

Authentic:

Cardiovascular flow rates and aortic valve pressure gradients

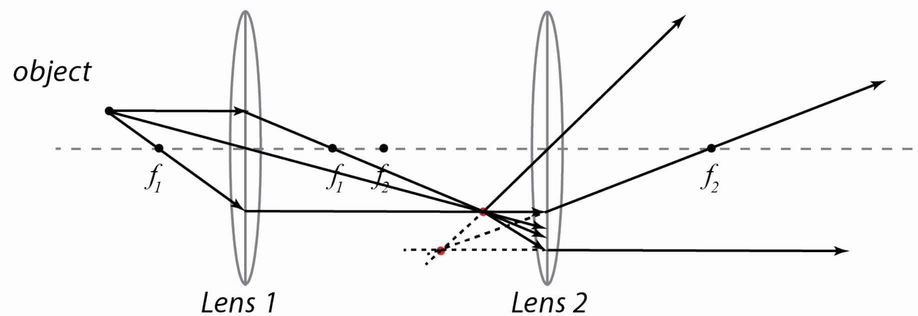


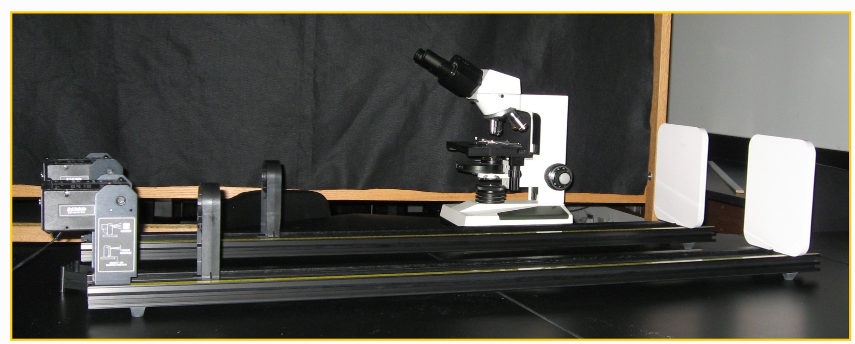
# Authentic life science connections

Physics contributes understanding that is meaningful to life scientists

*Marginal:*

Microscope design



# Authentic life science connections

Physics contributes understanding that is meaningful to life scientists

*Inauthentic*:

Textbook kinematics problem with a car replaced by a cheetah

# Consult deeply with life science/ medical experts

Advisory committee

Rachel Merz
marine biologist
biomechanics

Kathy Siwicki
neurobiologist

Liz Vallen
cell biologist

Sara Hiebert Burch
physiologist

Kathleen Howard
biophysical chemist

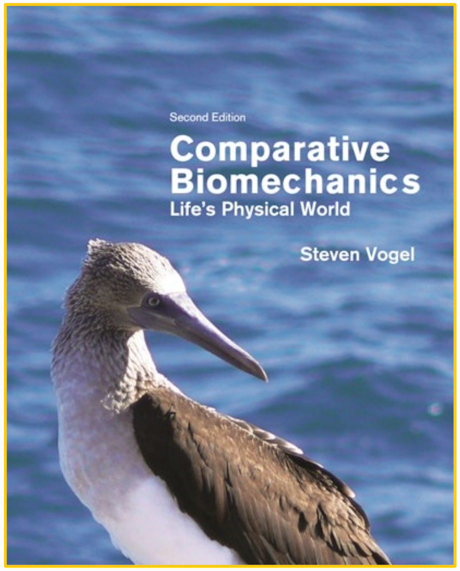
Stephen Miller
structural biologist

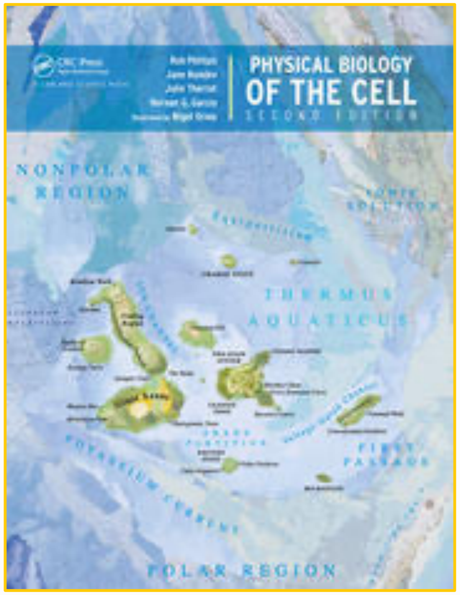
Co-developer,
fluid dynamics
unit and ECG lab

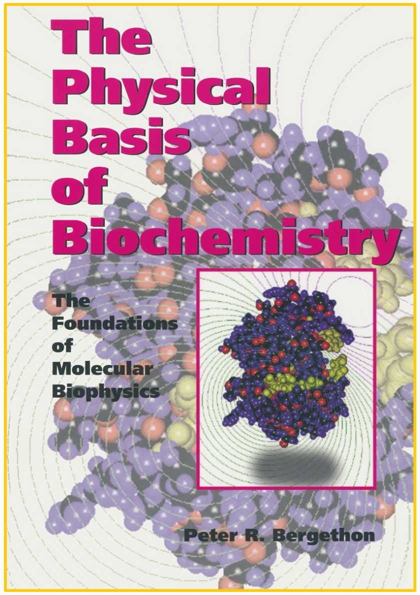
John Hirshfeld
cardiologist

(Penn School of Medicine)

# Consult deeply with life science/ medical experts



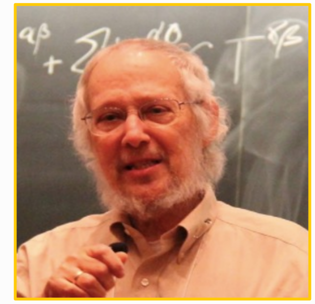



# Share ideas









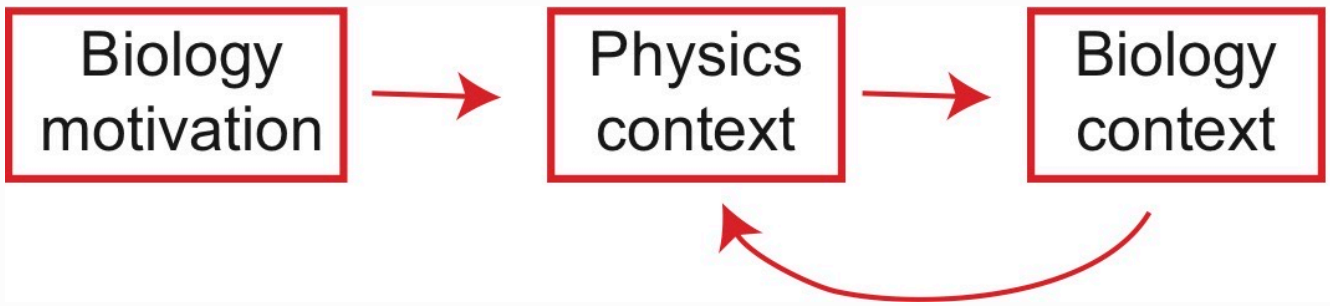

## *Backwards design process*

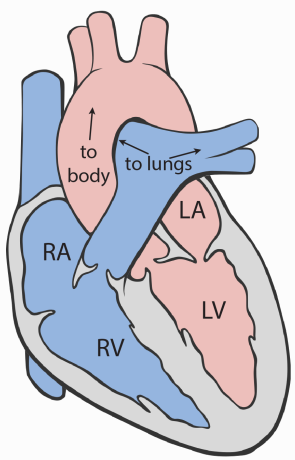
Begin with desired outcomes:

- Students develop knowledge and skills valuable for their chosen fields
- Students recognize that value
- Students feel valued and respected as learners

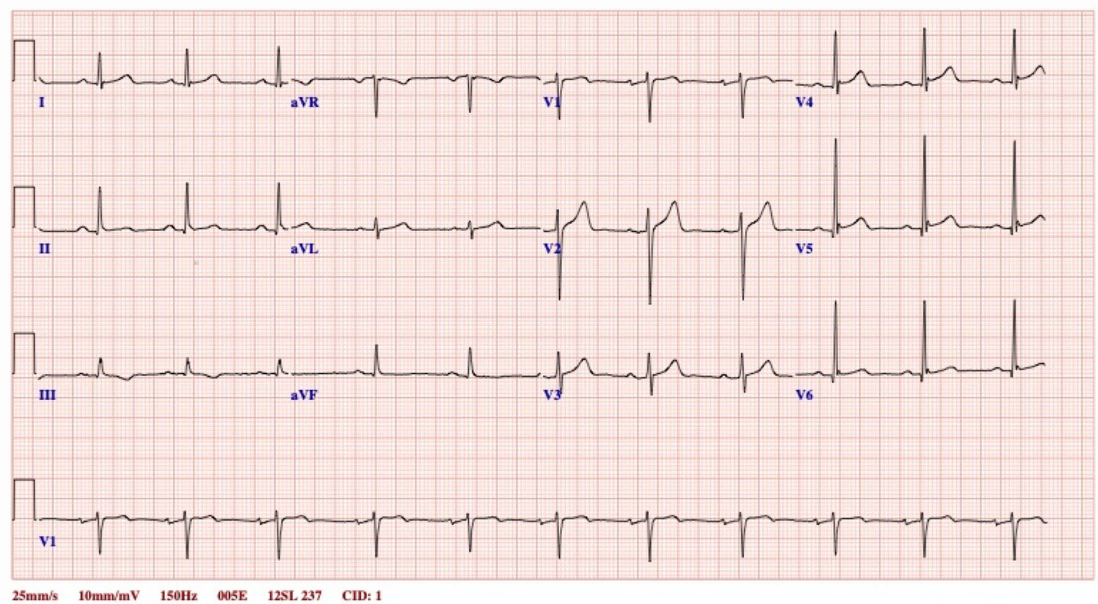
## *How do we help students recognize value?*

# Build units around connection(s)




*Heart drawn by Patrick Lynch, CC BY 2.5. Annotated by CHC.*



*Biological connections are integral, not tacked on*

# Expansive framing

HS students tutored about circulatory system

Two different framings:

- Restricted to the class
- Broadly relevant/applicable

Later study of respiratory system:

students tutored with broadly relevant framing applied previous lesson more successfully

*Engle, Nguyen, and Mendelsohn,* Instructional Science 39, *603 (2011).*

# Summary of design strategy

- Identify authentic connections in partnership with disciplinary experts
- Build course around those connections
- Tell as well as show the value of what students learn
- Use validated pedagogy!

*Does it work?*

1. Course design
2. Course outcomes

NSF 1710875, 2142074

# Research team

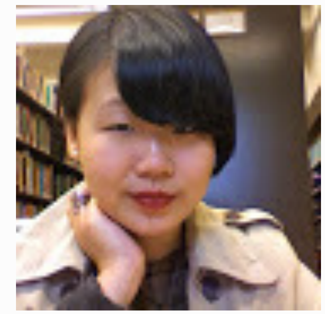
Panchompoo Wisittanawat '13

Ben Geller

Chandra Turpen

Sara Hiebert Burch (Biology)

K. Ann Renninger (Ed. Studies)



Ming Cai '11

Jack Rubien '20

Aqil Tarzan MacMood '20

Maya Tipton '23

Gwendolyn Rak '22

Jonathan Solomon '20

Nathaniel Peters '18

# Physics education research

Combine

- quantitative (statistical) analysis of data acquired from surveys, closed response instruments
- qualitative analysis of student work on open-ended tasks (questions or problems), interviews, observations

# Research questions

1. *How does IPLS affect student attitudes to, interest in and value for physics?*
2. *How well do students learn the material?*

# Student attitudes

CLASS survey given pre and post instruction:

42 statements about learning physics (6 or more probing interest)

1. A significant problem in learning physics is being able to memorize all the information I need to know.
2. When I am solving a physics problem, I try to decide what would be a reasonable value for the answer.
3. I think about the physics I experience in everyday life.

Respond with level of agreement (5 point scale)

Responses categorized as more or less expert-like

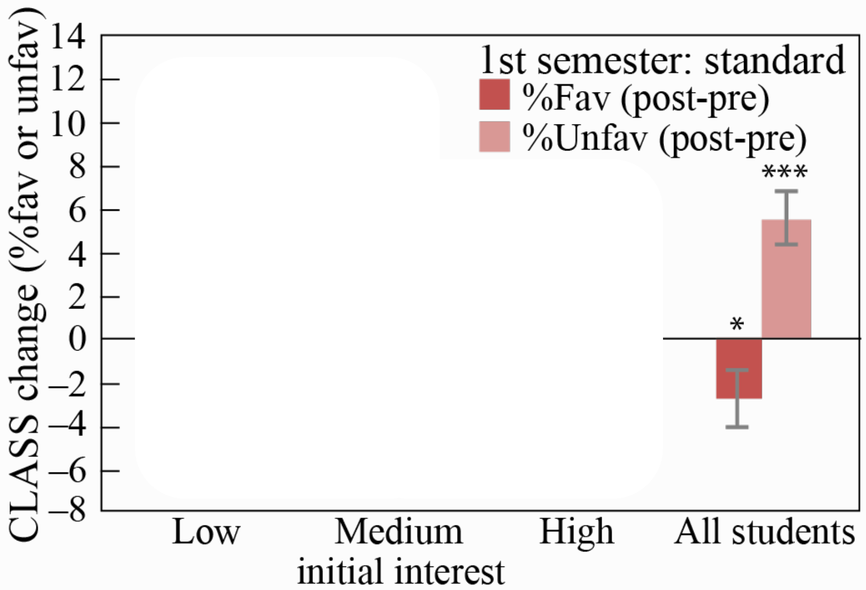
# Natural experiment

For 2008-2014, only 2nd semester of IPLS was reformed

Compared pre/post responses from *same students* in

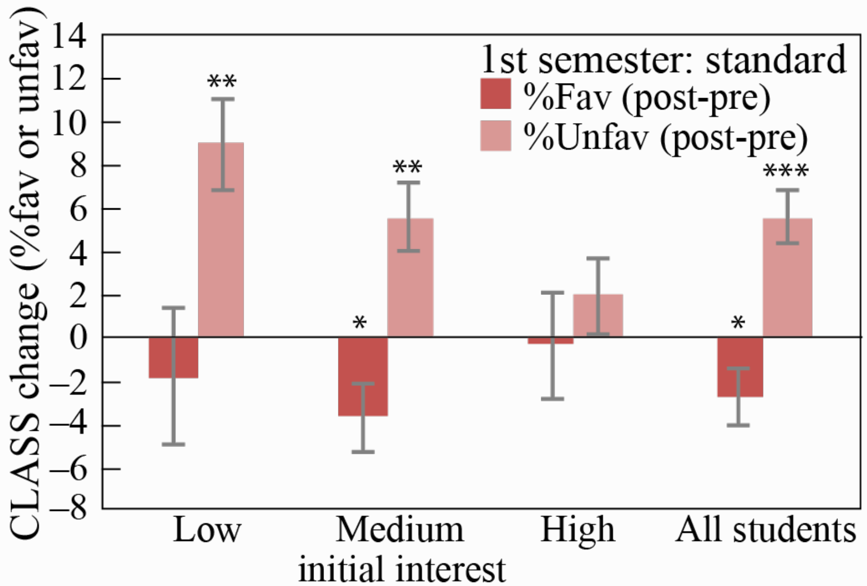
- first semester of standard mechanics
- second semester of IPLS E&M

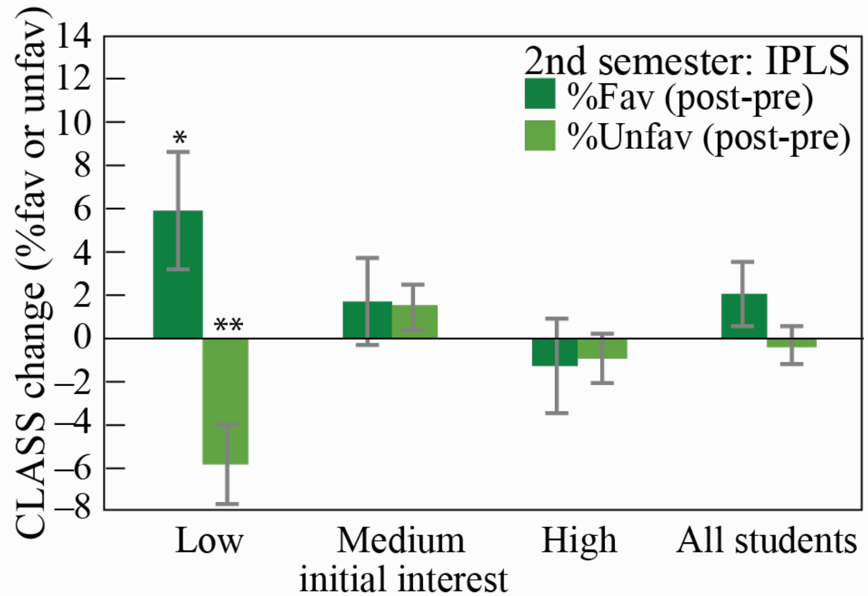
# Changes in CLASS




Standard course: attitudes decline (normal)

# Changes in CLASS




Standard course: attitudes decline in standard course (normal)
IPLS course: Hold steady/improve for students with low initial interest

*Crouch, Wisittanawat, Cai, and Renninger,* Phys Rev PER 14, 010111 (2018).

Compared to teaching the same physics without the life science examples, by including these examples, Physics 4L was:

# Relevance

Students respond to 3 Likert items about connections between physics and biology

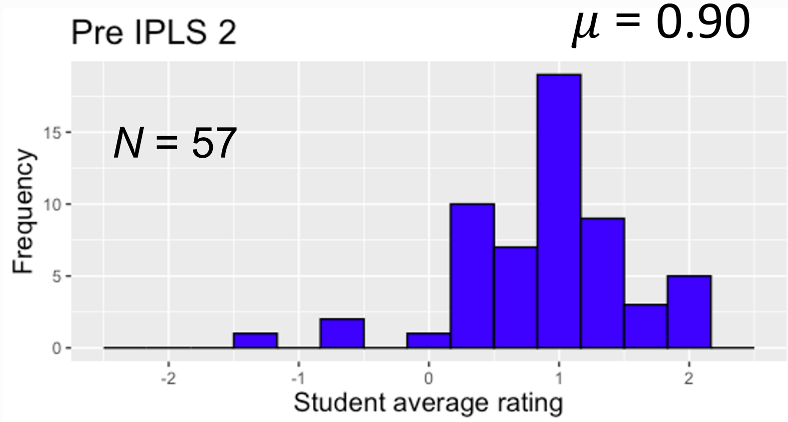
*Items from K. Hall, Ph.D thesis, UMd* (2014).

# Relevance of physics pre/post IPLS

Gwendolyn Rak ’22

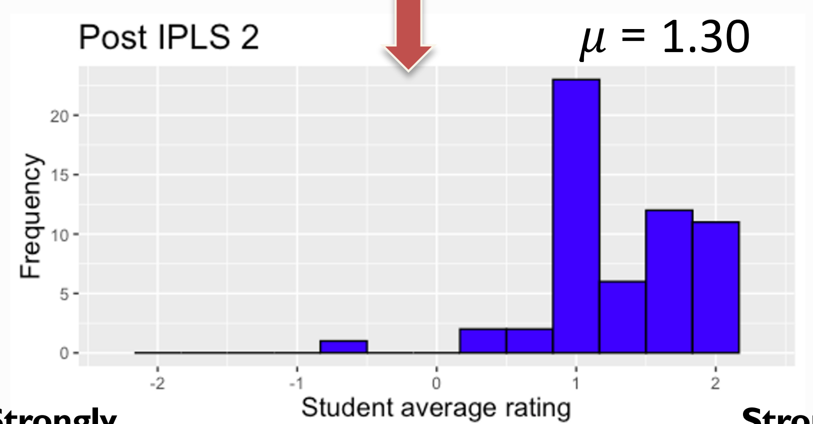
PRE

**Before IPLS**




POST

**Immediately after IPLS**




**Strongly unfavorable**

**Strongly favorable**

Students view physics as much more connected to biology after one semester of IPLS

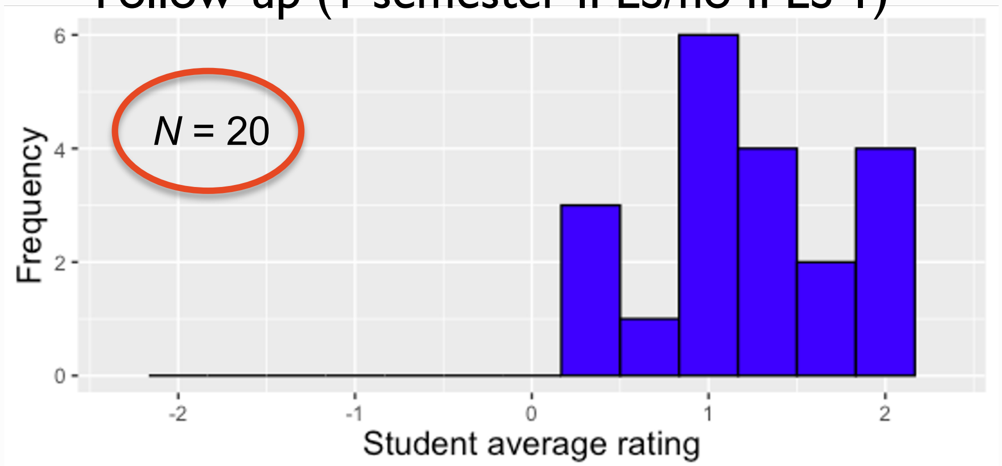
$p = 3.9 \times 10^{-5}$

(Wilcoxon signed-rank test)

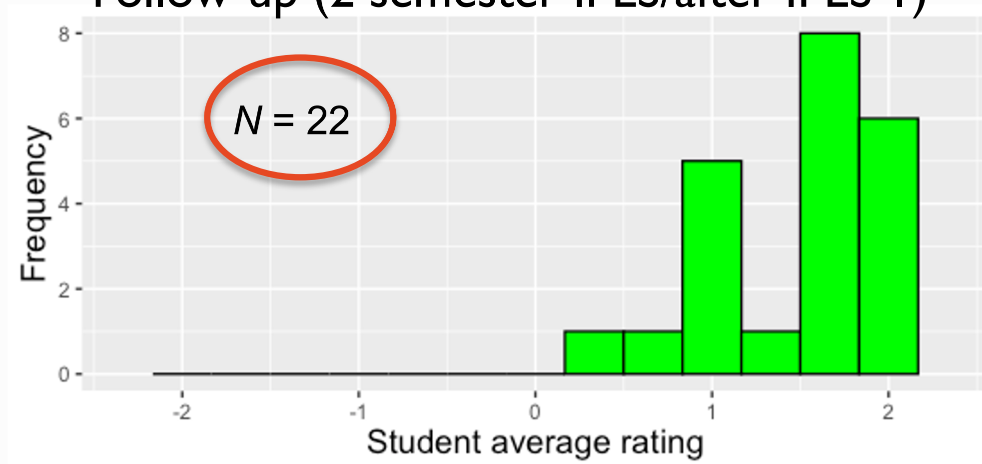
*Items from K. Hall, Ph.D thesis, UMd* (2014).

# Greater relevance persists one year later

Follow-up (1 semester IPLS/no IPLS 1)




Follow-up (2 semester IPLS/after IPLS 1)



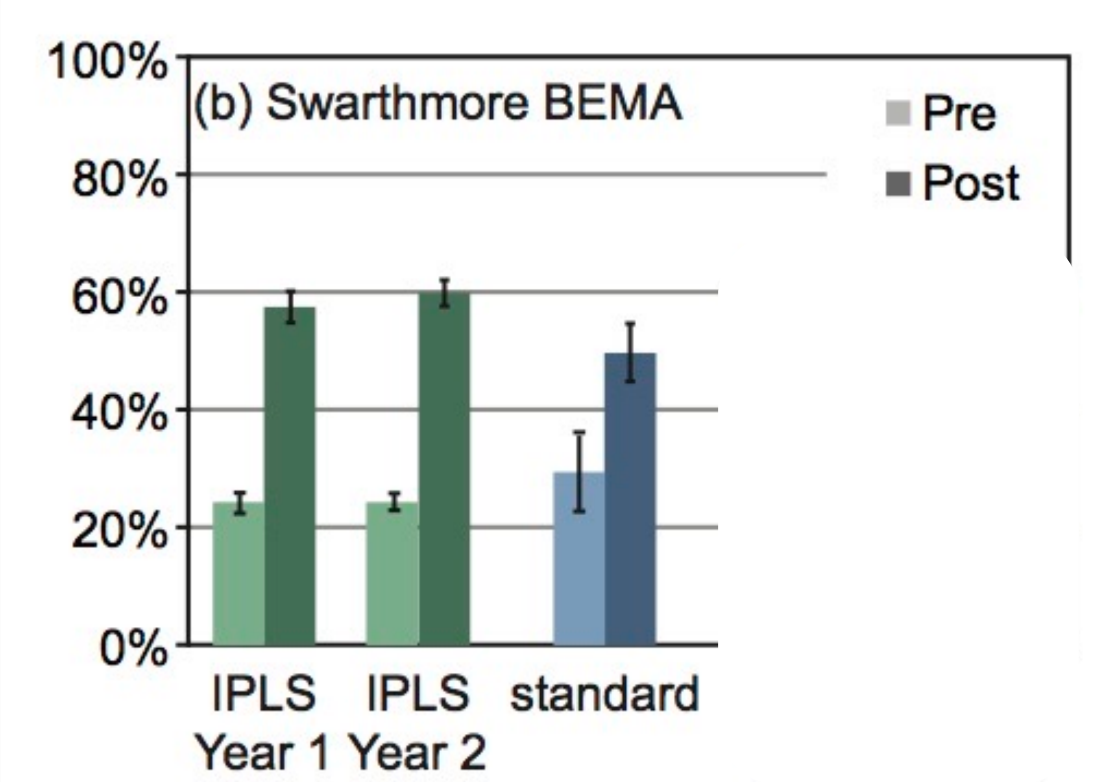

**Follow-up: $\mu$ = 1.22**
Post: $\mu$ = 1.30
} $p$-value=0.54

**Follow-up: $\mu$ = 1.49**
Post: $\mu$ = 1.47
} $p$-value=0.92

# Research questions

1. *How does IPLS affect student attitudes to, interest in and value for physics?*
2. *How well do students learn the material?*

# Physics understanding: E&M




*Crouch and Heller,* Am. J. Phys. **82**, *378 (2014).*

# Research questions

1. *How does IPLS affect student attitudes to, interest in and value for physics?*
2. *How well do students learn the material? Can students use physics to analyze a biological situation?*

*Need to set up better how modeling is a key goal of the course somewhere and then capitalize on it here*

Maya
Tipton ’23

# Compare physical modeling of biological systems at end of mechanics semester

| life science students, **IPLS mechanics** | life science students, **standard mechanics** |
| --- | --- |
| $N = 61$ | $N = 37$ |

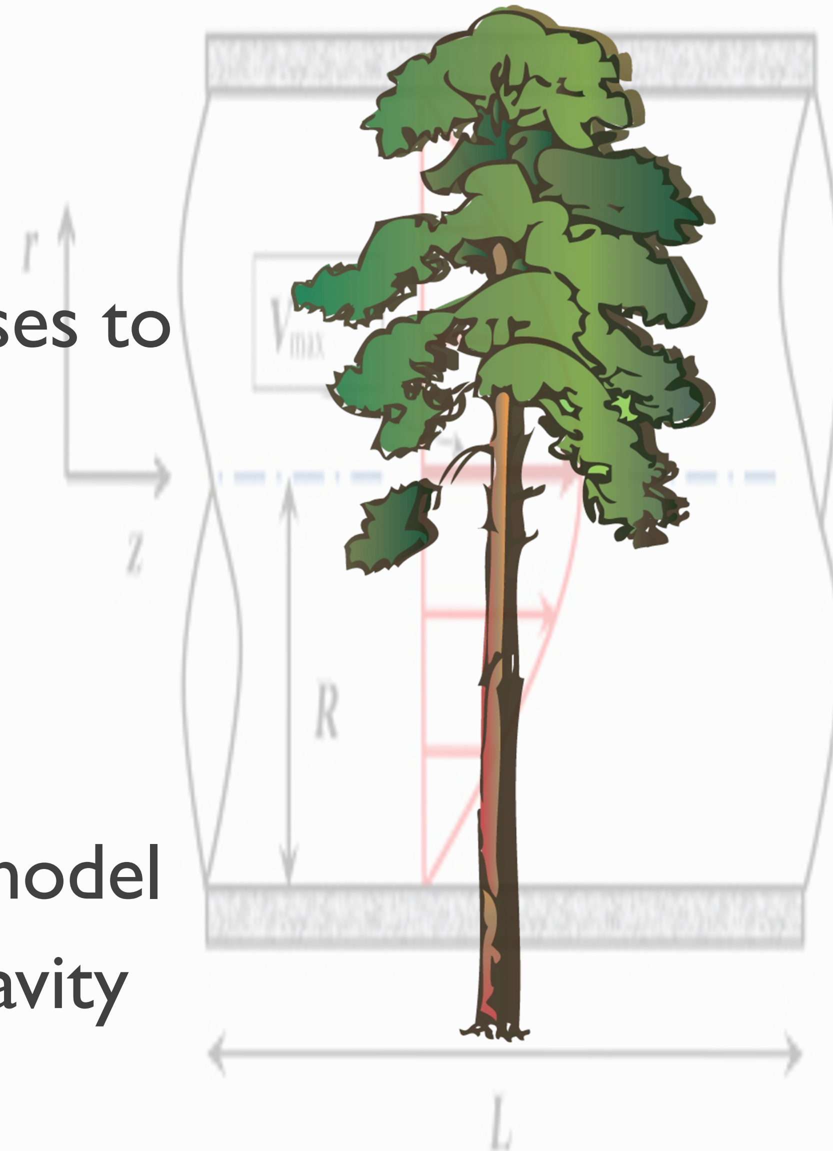
*Thanks to Eugenia Etkina, Rutgers

# Task Design

Use physics studied in both courses to **model an unfamiliar biological situation**

Sap fluid dynamics:

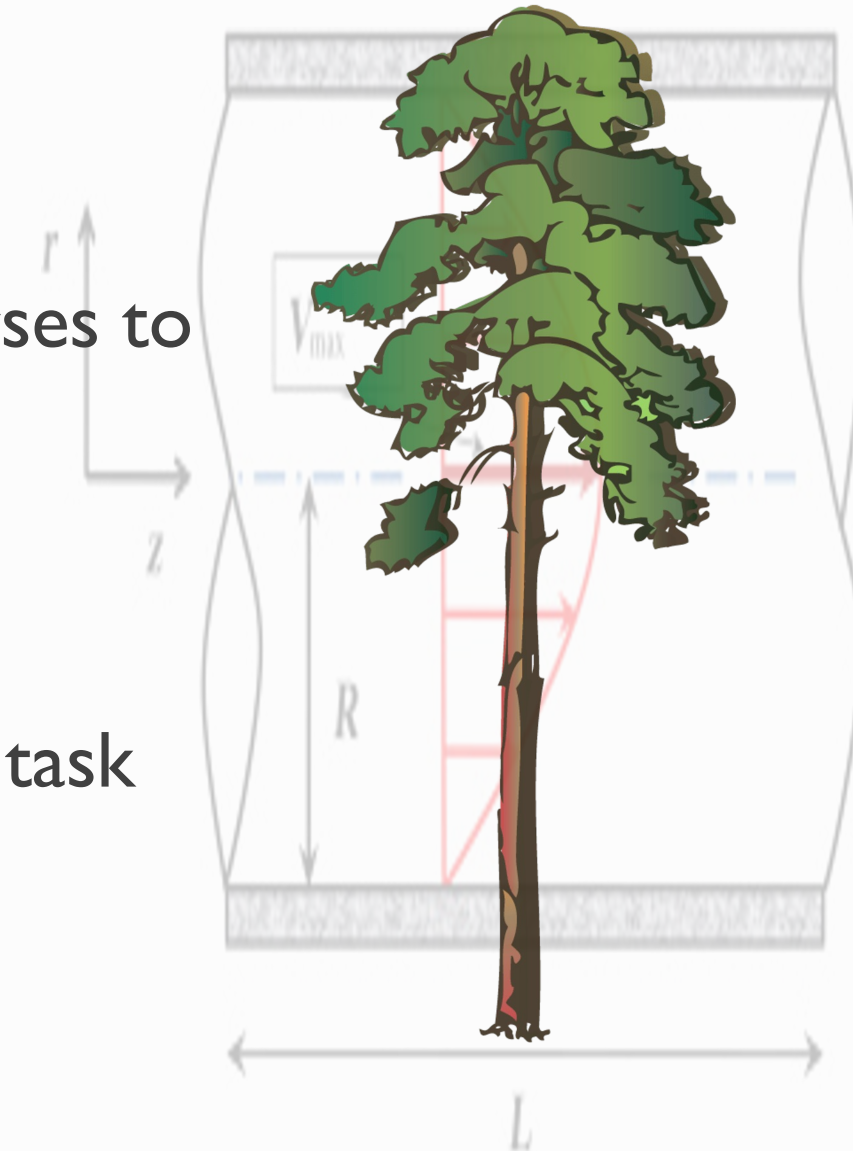
- choose viscous or nonviscous model
- combine viscous model with gravity



# Task Design

Use physics studied in both courses to **model an unfamiliar biological situation**

Also gave non-biological control task



# Identifying modeling in student work

Three different researchers developed an emergent code for key modeling and problem-solving competencies

- Model justification
- Flexible coordination of physical models
- Units and calculation

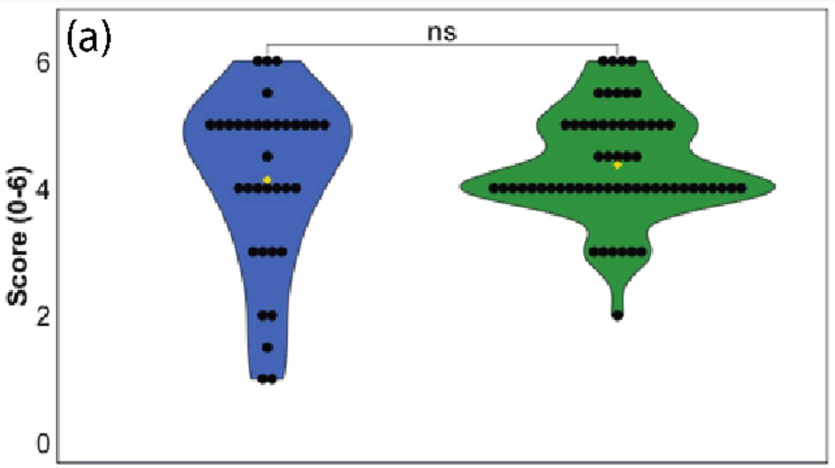
Inter-rater reliability: 0.94

Geller, Tipton, Daniel-Morales, Tignor, White, and Crouch., *PRPER* **18,** 010131 (2022)

# Both groups use basic fluid statics comparably

Nikhil Tignor '24 Rain White'24 Brandon Daniel-Morales '24

Standard fluid statics problem



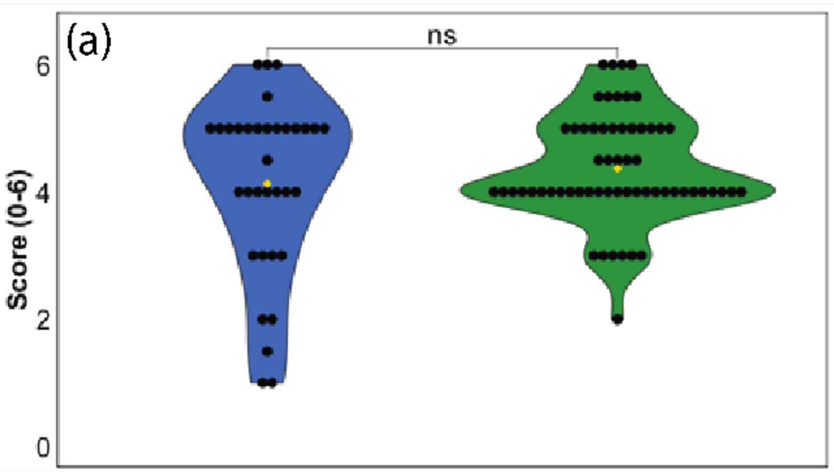

**NO IPLS (N = 34)** **IPLS (N = 61)**

Geller, Tipton, Daniel-Morales, Tignor, White, and Crouch., *PRPER* **18,** 010131 (2022)

# Both groups implement simple models with comparable success

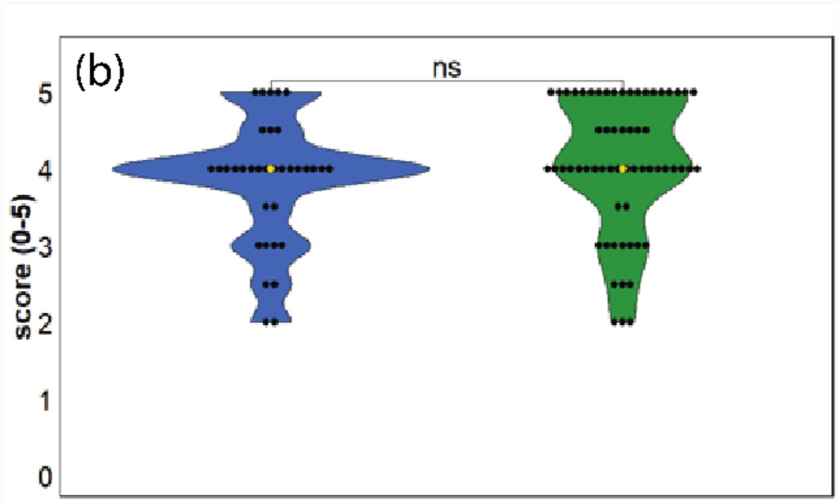
Nikhil Tignor '24 Rain White'24 Brandon Daniel-Morales '24

Standard fluid statics problem




**NO IPLS (N = 34)** **IPLS (N = 61)**

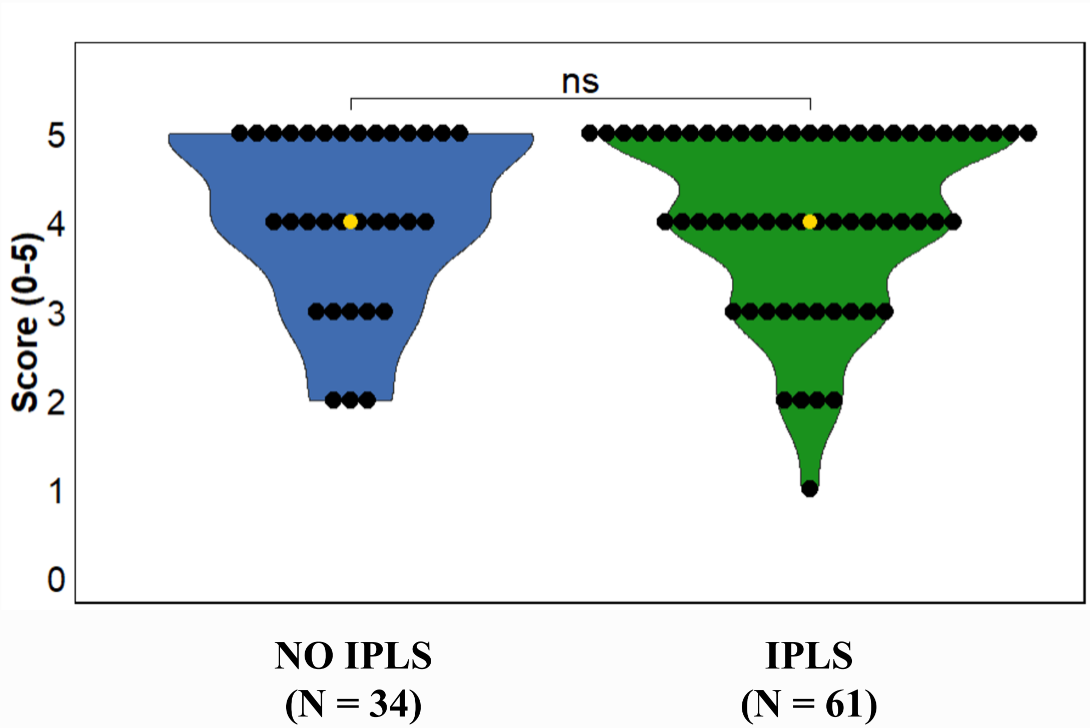
Standard thermodynamics problem




**NO IPLS (N = 34)** **IPLS (N = 61)**

Geller, Tipton, Daniel-Morales, Tignor, White, and Crouch., *PRPER* **18,** 010131 (2022)

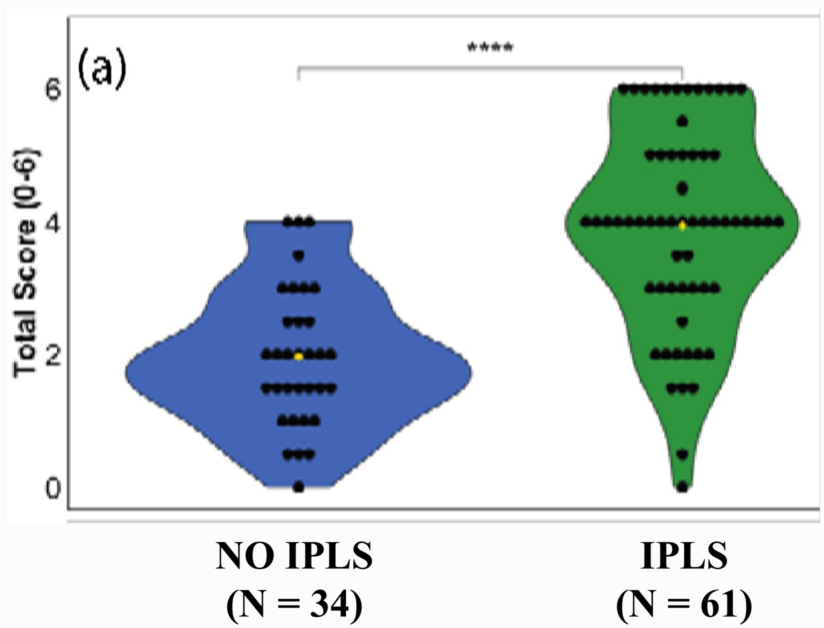
# Both groups display comparable calculation/numerical skill




Geller, Tipton, Daniel-Morales, Tignor, White, and Crouch., *PRPER* **18,** 010131 (2022)

# BUT IPLS students were significantly stronger at combining models flexibly and justifying them

Total score on modeling parts




Geller, Tipton, Daniel-Morales, Tignor, White, and Crouch., *PRPER* **18,** 010131 (2022)

# Biology Capstone Task*

Biology capstone required for seniors

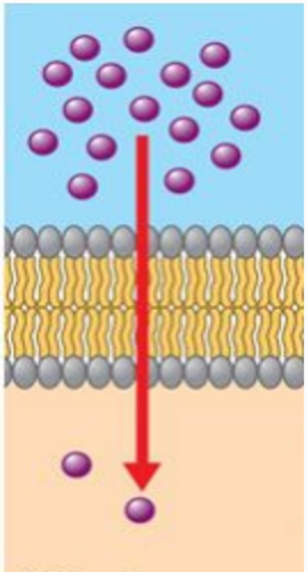
- ~60% took at least *some* IPLS, others standard or HS physics
- ~40% took IPLS 1 specifically

Task was part of assessing biology "quantitative requirement"

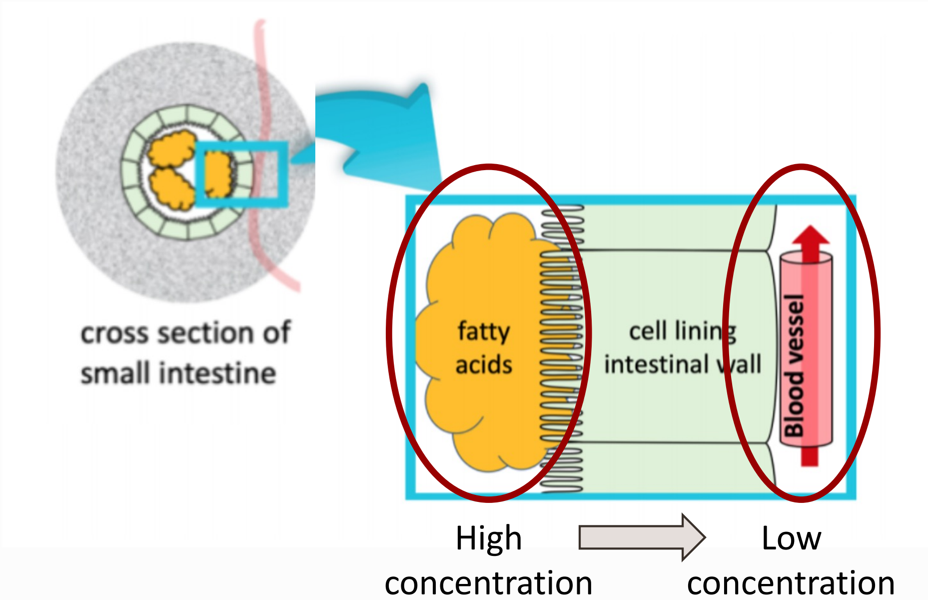
* Thanks to Michelle Smith, Cornell Biology Education

# Diffusion Task

- Central physical concept for biology
- Taught phenomenologically (quantitatively) in Bio 1 and 2
- Taught mechanistically in IPLS 1



# Diffusion Task




- Graph fatty acid concentration vs. position
- Describe the mechanism of diffusion
- Compare graphs, evaluate slopes
- Apply and reason using Fick's Law

# Code for capstone task.

| Part I | | |
|---|---|---|
| Skill | Evidence of skill | Rubric |
| *Converting a written description of a biophysical scenario into a qualitatively accurate graph* | *Sketch of a graph that shows the fatty acid concentration to be constant in the intestine and the blood vessel, but linearly decreasing in the cell lining the intestinal wall* | • Ends: +0.5 for each constant (horizontal) end of the sketched line<br>• Middle (QUANT): +2 points if linearly decreasing; +1 if decreasing, but not linearly<br>• For bar plot or scatter plot instead of a continuous graph: +1 if trend is correct |
| *Providing a mechanistic, molecular-level explanation for the flow of molecules down a concentration gradient* | *Mechanistic explanation for the net flow of particles from high to low concentration in terms of the difference in number of particles moving randomly in different regions of the system, along with a supporting diagram.* | Explanation (IPLS 1):<br>• +2: Difference in number of molecules between high and low concentration regions used to provide a mechanism for the net flow of particles, even though each individual molecule moves randomly<br>• +1: Explains the flow in terms of general physical reasoning (collisions, thermodynamics, Fick's law), but does not employ a complete mechanistic explanation<br>• 0: Restates the question or no coherent explanation<br>Diagram (IPLS 1):<br>• +1: Diagram demonstrates why more molecules move across a boundary from high to low concentration than from low to high concentration<br>• +0.5: Diagram is present, but does not clearly articulate the above idea<br>• 0: No diagram |

| Part II | | |
|---|---|---|
| Skill | Evidence of skill | Rubric |
| *Calculating rates of diffusion from graphical representations of concentration as a function of position.* | *Calculation of slopes from the data provided, and comparison of these slopes to rank diffusion rates* | Correctness (QUANT):<br>• +2: Completely correct ranking: $B > A = D > C$.<br>• +1: Slope $B$ is steepest and slope $C$ is least steep, but slopes $A$ and $D$ are not identified as having the same slope<br>• 0: Other ranking<br>Slope reasoning (QUANT):<br>• +2: Correct reasoning with slopes<br>• +1: Incorrect calculation or incomplete explanation with slopes<br>• +0 + 0: No evidence of reasoning with slopes |

| Part III | | |
|---|---|---|
| Skill | Evidence of skill | Rubric |
| *Relating the mathematical expression of Fick's law to the physical process of molecules moving from areas* | *Explanation that explicitly relates the minus sign in Fick's law to the direction of molecular movement through the concentration gradient* | • (QUANT) +1: The minus sign is needed to specify direction of flux |

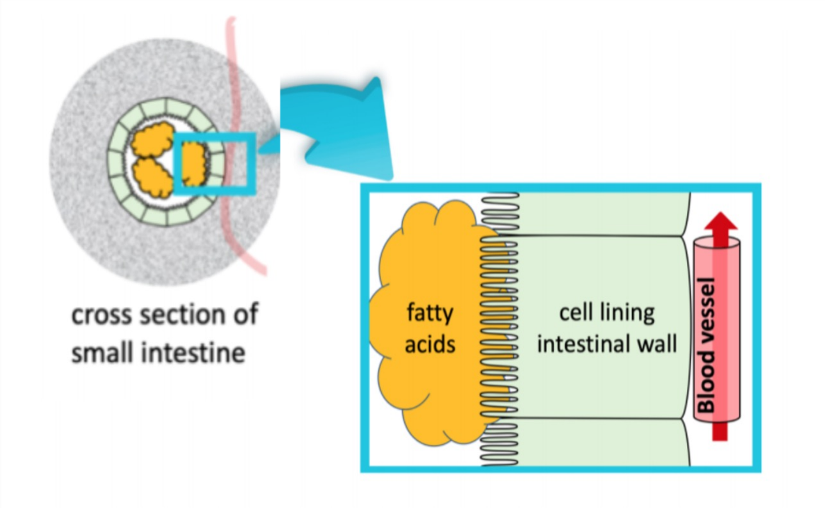



TABLE II. *(Continued)*

| Part I | | |
|---|---|---|
| Skill | Evidence of skill | Rubric |
| *Converting a graphical representation of diffusion into a quantitative, symbolic representation (Fick's law) that can be applied to obtain a quantitative result* | *Using Fick's Law to calculate a rate of flux, including appropriate units, from graphical data provided; explicitly coordinating the minus sign in Fick's law with a spatial direction* | End regions (QUANT):<br>• +1: Identifies the ends as $J = 0$<br>Middle region (QUANT):<br>• +1: Calculation for the middle as $J = 10\,000$ molecules/s<br>• +1: Positive sign obtained by correct use of Fick's law<br>Holistic over all of Part III (IPLS 1):<br>• +2: Coordinates the positive sign to the direction of flow along the $x$ axis<br>• +1: Attempts to relate the sign to the coordinate system, but unsuccessfully |

# Emergent coding scheme

**Content and Skills Emphasized in IPLS 1**

- Mechanistic description of diffusion
- Coordinating multiple representations of diffusion
- Coordinating the sign of particle flux with a direction in space

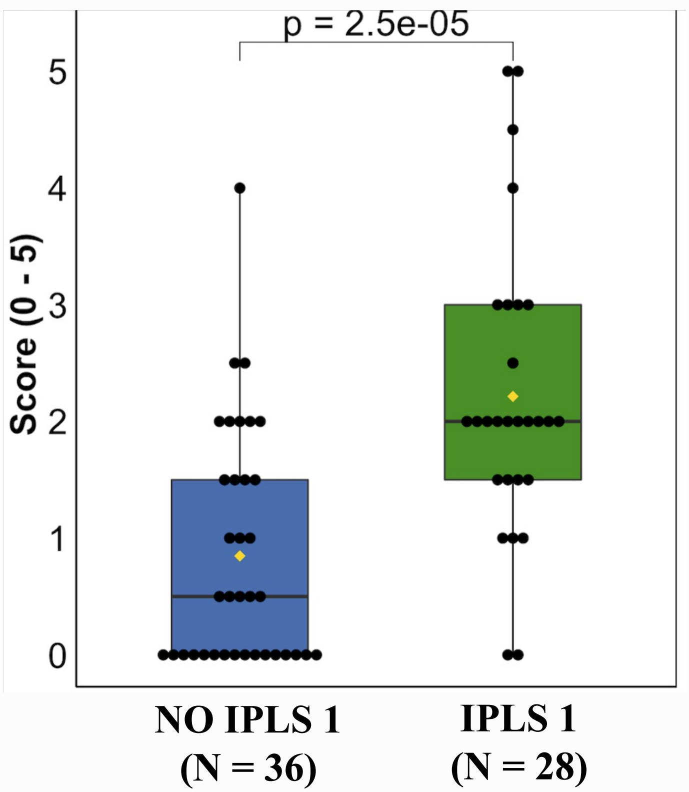
**General Quantitative Skills Emphasized in IPLS (and elsewhere)**

- Draw linearly decreasing graph
- Compare graphs by their slopes
- Use equations to calculate relevant quantities
- Reason with units

Jack Rubien ’20

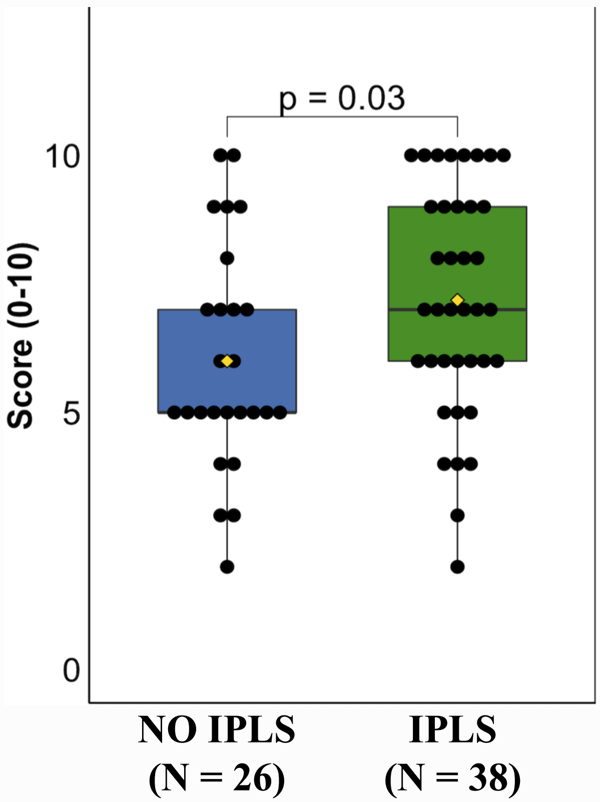
Cohen’s kappa > 0.8 for all elements

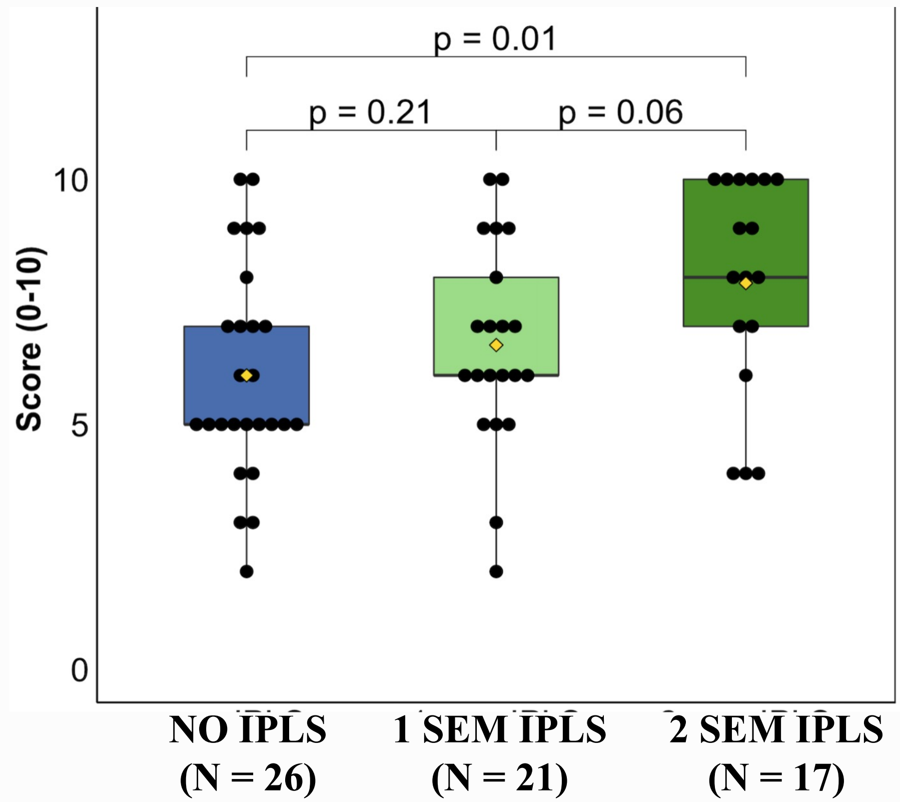
# Content and skills emphasized in IPLS 1




Geller et al., *PR-PER* (2022)

# General quantitative skills




Geller et al., *PR-PER* (2022)

# Are IPLS students just higher performing?

## NO

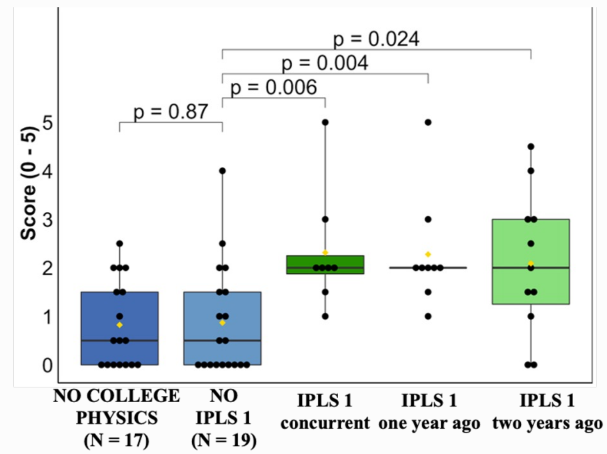
IPLS students had lower overall GPA in STEM courses than the non-IPLS students.

| Code elements | Observed difference in mean $\Delta\mu$ | Adjusted difference in mean |
|---|---|---|
| *IPLS 1-specific* | $\mu_{\mathrm{IPLS1}} - \mu_{\mathrm{non\text{-}IPLS1}} = \mathbf{1.36}$ | 1.50 (+**0.14**) |
| *General quantitative* | $\mu_{\mathrm{IPLS1}} - \mu_{\mathrm{non\text{-}IPLS1}} = \mathbf{1.18}$ | 1.19 (+**0.01**) |

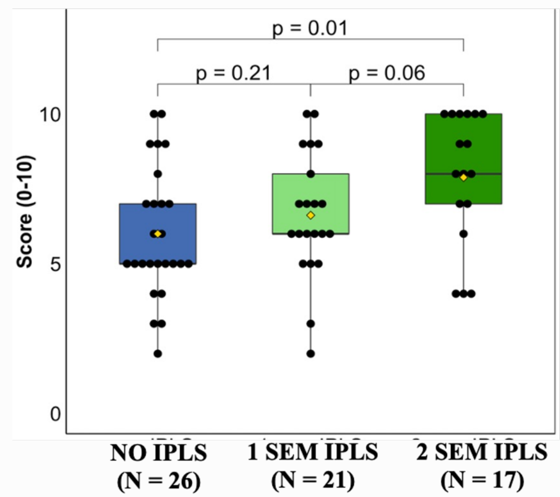
Geller et al., *PR-PER* (2022)

Conclusions:

**IPLS 1 students successfully reason about diffusion in a novel biological context, even after 2+ years.**




**IPLS students demonstrate greater proficiency with quantitative reasoning in a biological context**



# Take-homes: outcomes

- Student interest, perception of value, and broad attitudes improve
- Improved attitudes persist for at least a year
- Students more successful in flexibly combining models for an unfamiliar biological phenomenon (than standard mechanics)
- A year or more later, students use what they learned on a biological task

# Take-homes: Design strategy

- Identify authentic connections in partnership with disciplinary experts
- Build course around those connections
- Tell as well as show the value of what students learn
- Use validated pedagogy!

# Thanks to …

NSF 1710875, 2142074

NSF, HHMI, and Mellon grants

Faculty colleagues:

Ben Geller, Ann Renninger (Swarthmore)

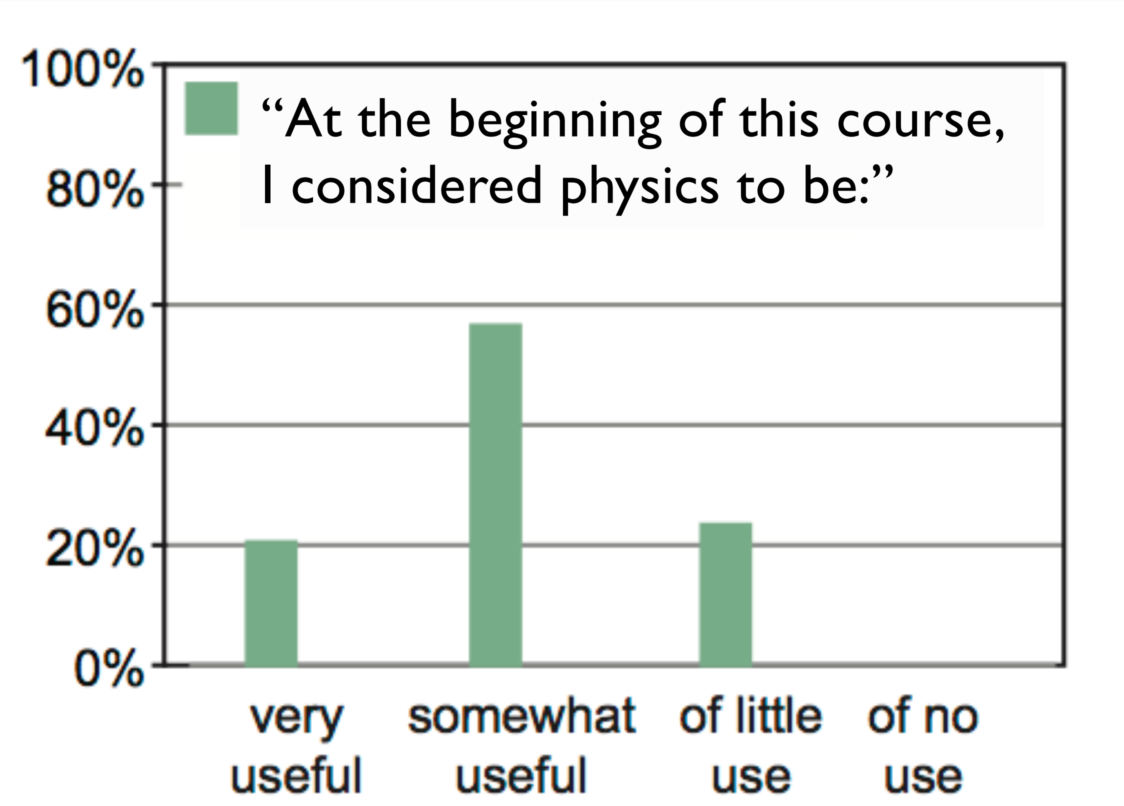
*Biology*: Sara Hiebert Burch, Shannon Ballard, Nick Kaplinsky, Rachel Merz, Kathy Siwicki, Liz Vallen

*Biochemistry*: Kathleen Howard, Stephen Miller

*Medicine*: John W. Hirshfeld Jr, MD

Eugenia Etkina (end of semester task), Michelle Smith (bio capstone task)

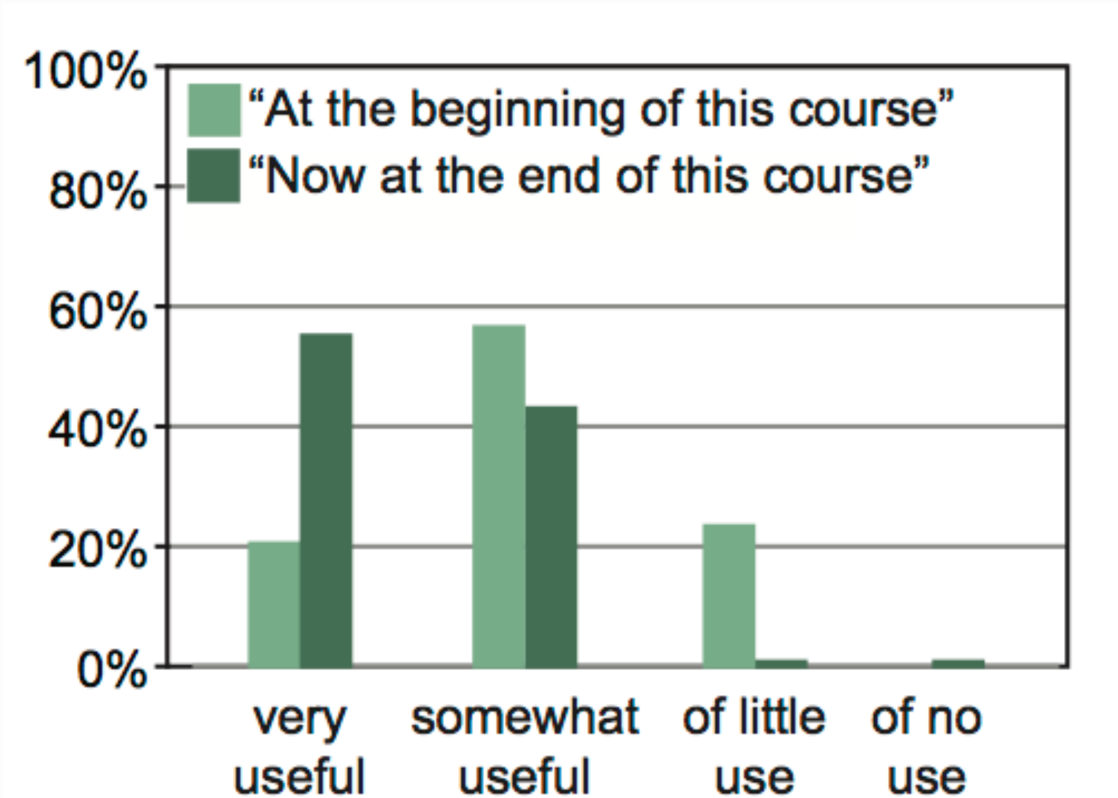
# 2012 course evaluation (*N* = 68)




*Question developed by UMD PERG*

….in understanding the life sciences.

# 2012 course evaluation (*N* = 68)




*Replicated in 2013 and 2014*
*(zero "of no use" responses)*

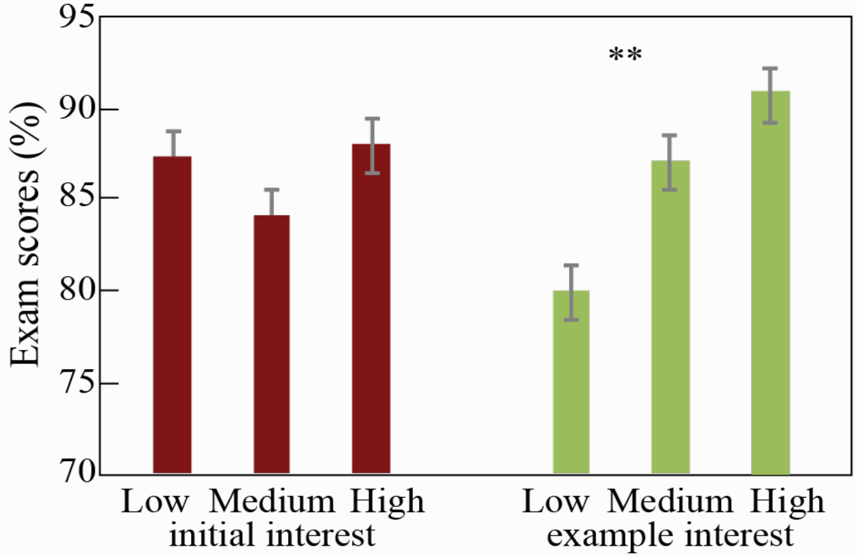
…. in understanding the life sciences.

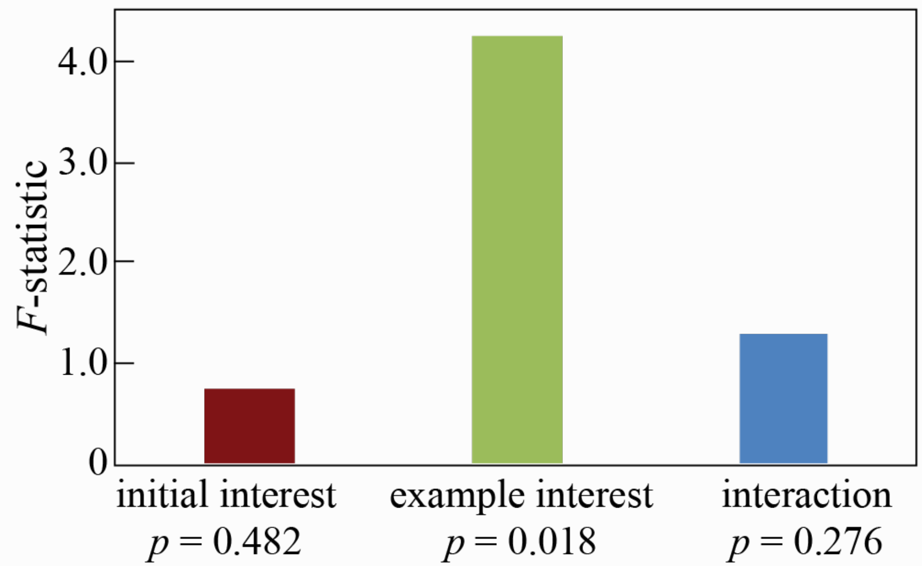
# Interest matters

Self-reported student interest in examples, more than pre-IPLS interest in physics, predicts IPLS exam scores

# Interest matters

Exam scores by initial interest (red) and example interest (green)



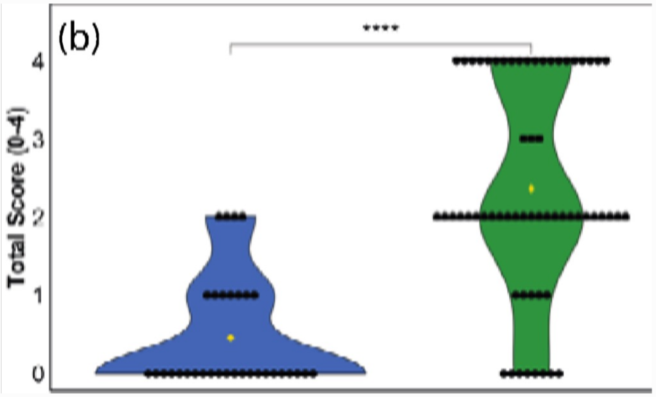




$$F = \frac{\text{explained variance}}{\text{unexplained variance}}$$

*Crouch, Wisittanawat, Cai, and Renninger,* Phys Rev PER 14, 010111 (2018).

IPLS students demonstrate **greater skill in flexibly combining and applying physical models in an unfamiliar biological context.**

- Viscous flow had never been considered in a vertical system
- IPLS and non-IPLS students showed similarly proficiency in employing simple models and in calculation/numerical skill



*Discuss with your neighbor:*

What do you find/expect is hard about teaching effective, enjoyable service courses?