Developing Physical Modeling Skills in Introductory Physics for the Life Sciences

CATHERINE H. CROUCH, SWARTHMORE COLLEGE

WITH MAYA TIPTON, BRANDON DANIEL-MORALES, RAIN WHITE, NIKHIL TIGNOR, AND BEN GELLER

AAPT EC-02, 9 JULY 2024

IPLS Goals

Help students become prepared and motivated to apply physics in future life science work

Do they?

“Prepared”: content and skills

Professional society recommendations

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

“Prepared”: content and skills

Teach physics content most connected to life sciences

Develop “physics toolkit”:

- modeling
- qualitative and quantitative reasoning,
- multiple representations,
- working with data

“Prepared”: content and skills

Teach physics content most connected to life sciences

Develop “physics toolkit”:

- modeling — including biological systems
- qualitative and quantitative reasoning
- multiple representations
- working with data

“Motivated”: relevance

Design principles for supporting relevance

- Foreground **authentic connections** between physics and the life sciences
- Expansive framing: Telling as well as showing the **lasting value of what students learn** promotes transfer and enduring learning
- Use validated pedagogy!

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

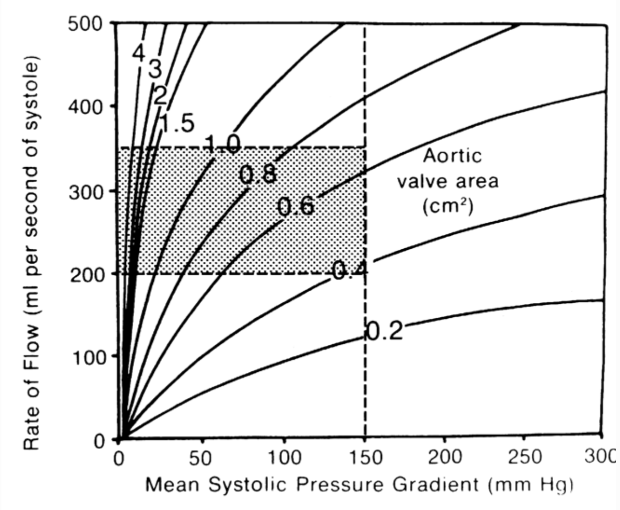
Engle, Nguyen, and Mendelsohn, Instructional Science 39, *603 (2011).*

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

Inauthentic:

Textbook kinematics problem with a car replaced by a cheetah

IPLS design process

- Partner with disciplinary experts to identify authentic connections

Partner with life science/medical experts

Swarthmore College 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

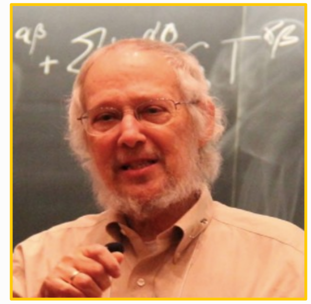
John Hirshfeld
cardiologist

(Penn School of
Medicine)

Share ideas







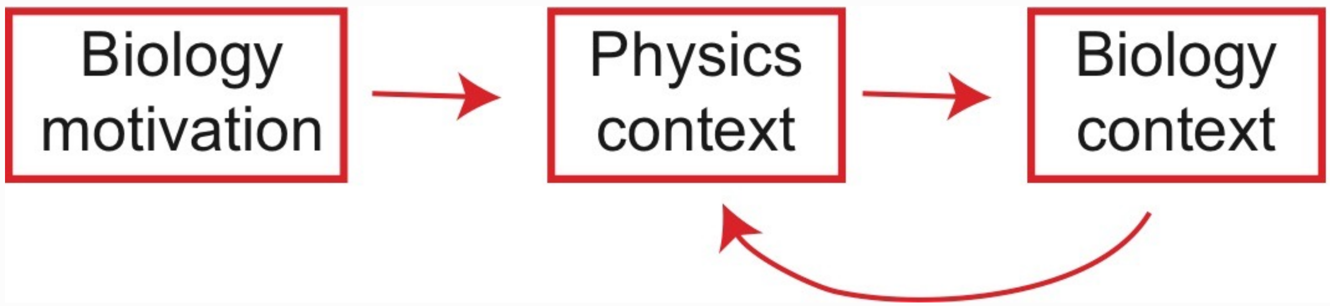


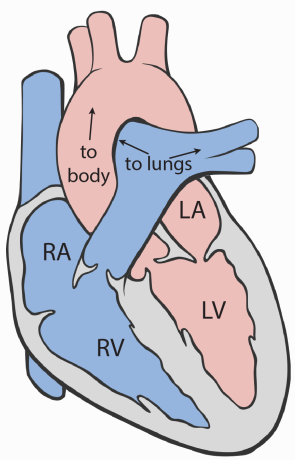


IPLS design process

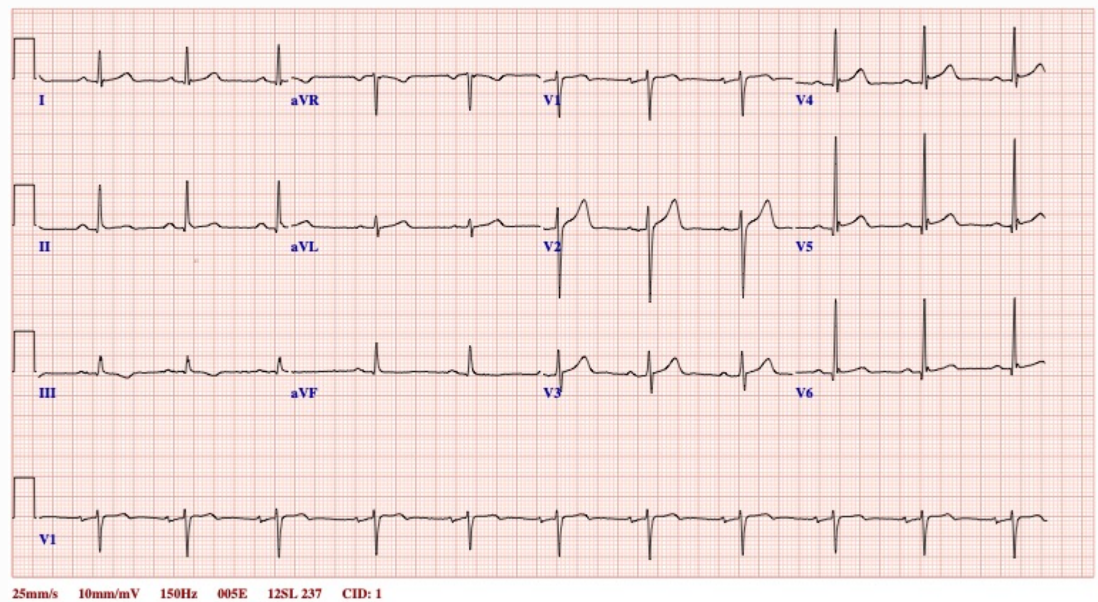
- Partner with disciplinary experts to identify authentic connections
- Build each course unit around connections

Build units around connection(s)





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

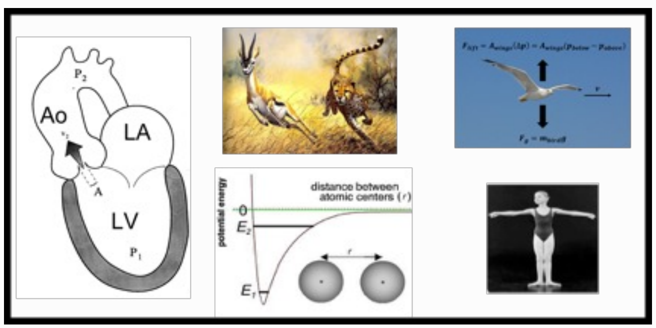


Biological connections are integral, not tacked on

Reformed content with biological contexts

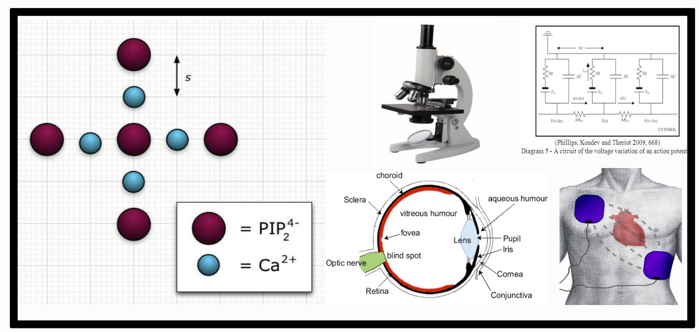
IPLS Mechanics

- Kinematics and Dynamics: ***random vs. coherent motion, biomechanical stability***
- Energy: ***chemical energy***
- Fluids: ***cardiology and flight***
- Thermo: ***heat conduction and free energy***



IPLS E&M

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



Swarthmore IPLS design summary

- Identify **authentic connections** by partnering with disciplinary experts
- Build course around those connections
- State the **lasting value of what students learn**
- Use validated pedagogy!

Does it work?

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 '24

Gwendolyn Rak '22

Jonathan Solomon '20

Nathaniel Peters '18

Research question

How well do IPLS students, and life science students with standard introductory physics, use physics to analyze an unfamiliar biological situation?

Natural experiment

For 2015-2019, IPLS mechanics (first semester) was offered only in odd years

Many life science students took standard mechanics in Fall 2018

We analyzed work on the same biological modeling task by life science students with and without IPLS

Maya
Tipton ’24

Compare student work on a task requiring physical modeling of a biological system given at end of mechanics course

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

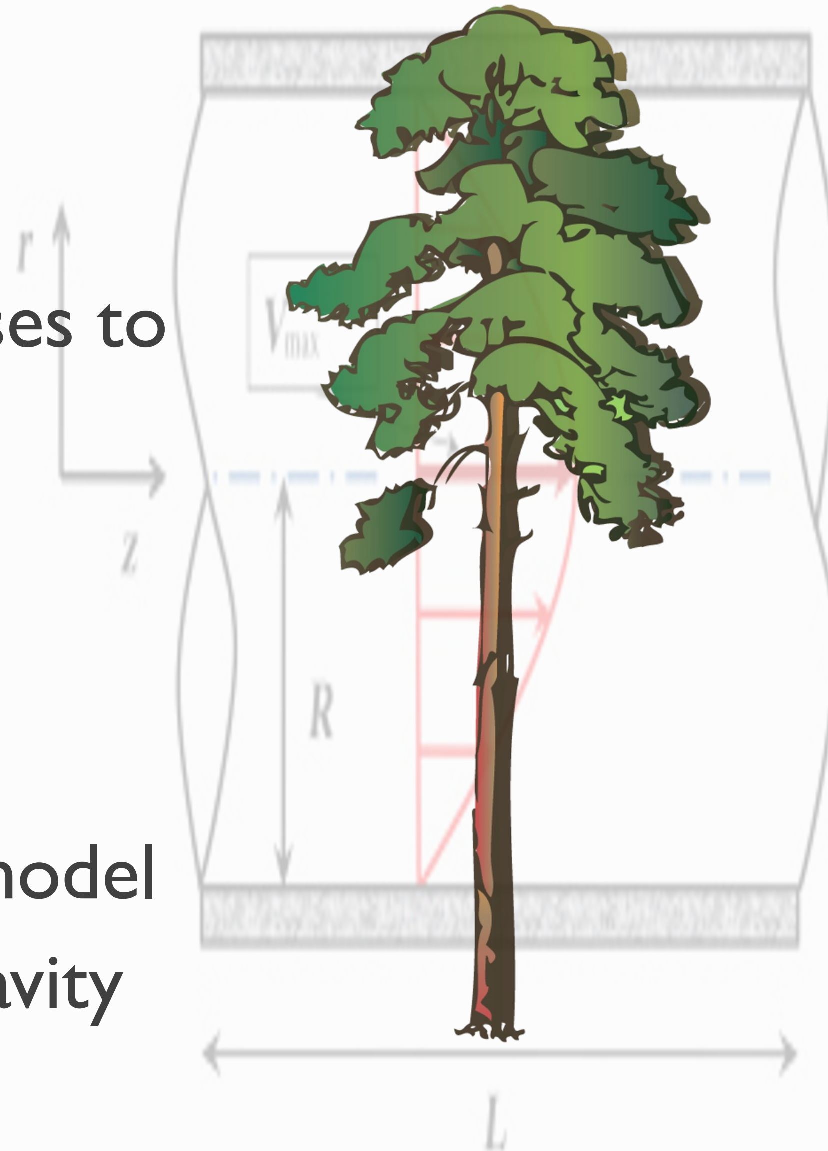
*Thanks to Eugenia Etkina, Rutgers

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

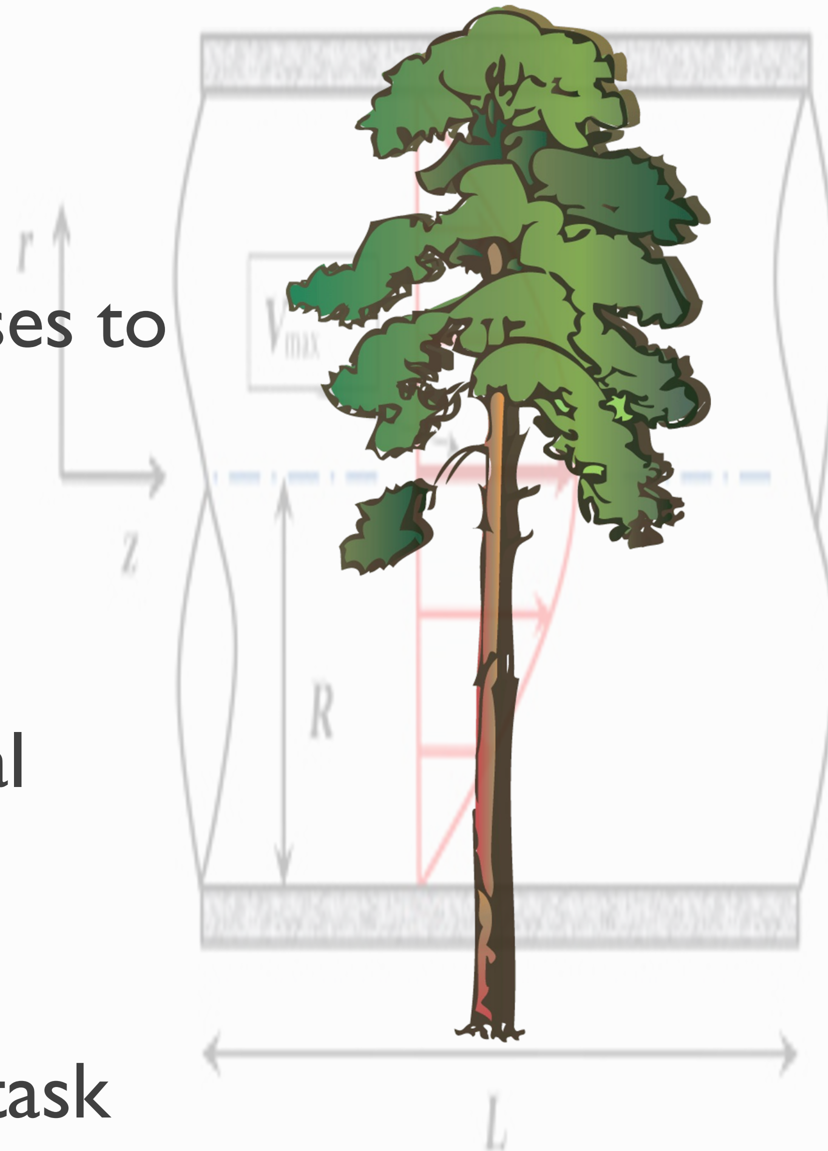


Task Design

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

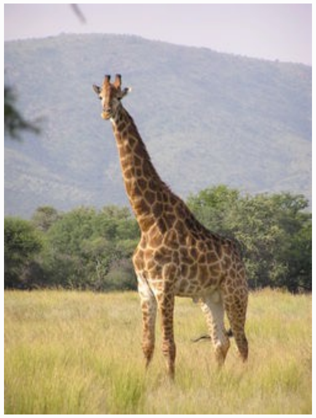
(Neither course discussed vertical viscous flow)

Also gave non-biological control task



Transfer task: part (a)

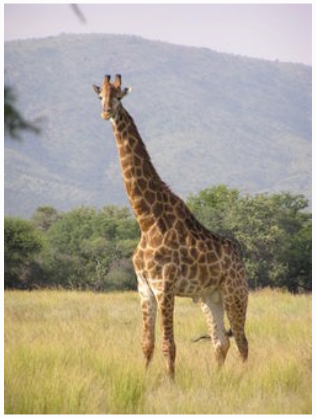
Adult male giraffes reach a height of roughly 6 m. The minimum pressure of the blood leaving the giraffe's heart is 1.24 atmospheres (124 kPa). Find an approximate value for the minimum blood pressure in the giraffe's brain when its neck is extended to its full height. You may infer information from the picture provided.



Please briefly explain your reasoning, including how you decided which equations to use, and any approximations you made.

Transfer task: part (a)

Adult male giraffes reach a height of roughly 6 m. The minimum pressure of the blood leaving the giraffe's heart is 1.24 atmospheres (124 kPa). Find an approximate value for the minimum blood pressure in the giraffe's brain when its neck is extended to its full height. You may infer information from the picture provided.



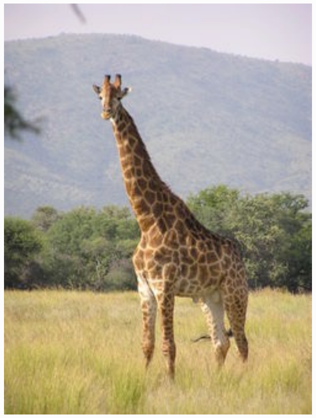
Please briefly explain your reasoning, including how you decided which equations to use, and any approximations you made.

Transfer task: part (a)

Adult male giraffes reach a height of roughly 6 m. The minimum pressure of the blood leaving the giraffe's heart is 1.24 atmospheres (124 kPa). Find an approximate value for the minimum blood pressure in the giraffe's brain when its neck is extended to its full height. You may infer information f

Purpose: to prime students to think about role of gravity in fluid pressure

Please briefl ... ling how you decided which equations to use, and any approximations you made.



Transfer task (part b)

In trees, water is carried from the roots to the leaves by the flow of sap through stiff tube-like structures, called xylem. A typical xylem diameter is 100 μm. In the main trunk of the tree, they extend close to the full height of the tree, which is commonly as great as 30 meters tall. These extremely narrow, long tubes contain a continuous column of water which can then flow into the leaves. Evaporation of water from the leaves (called transpiration) causes water to be steadily drawn up. The leaf structure allows the pressure of water in the xylem to not necessarily be the same as atmospheric pressure.

Transfer task (part b)

In trees, water is carried from the roots to the leaves by the flow of sap through stiff tube-like structures, called xylem. A typical xylem diameter is 100 μm. In the main trunk of the t … ll height of the tree, whi … neters tall. These extren … a continuous column of wa … e leaves. Evaporation … transpiration) causes water to be steadily drawn up. The leaf structure allows the pressure of water in the xylem to not necessarily be the same as atmospheric pressure.

- **Give dimensions of "stiff tube-like" vessels (xylem) through which sap flows**
- **Pressure at top doesn't have to be atmosphere**

Transfer task (part b, cont'd)

Consider a tree in which sap flows through each 100 μm-diameter xylem at a volume flow rate of 1.1×10^{-10} m^3/s (equal to 1.1×10^{-4} mL/s or 0.40 mL/hr), corresponding to an average flow speed of 0.014 m/s. If the pressure in the roots is equal to atmospheric pressure, what is the pressure at the top of a 30 m tall xylem in the trunk?

Please briefly explain the reasoning you used to find your answer, including how you decided which equations to use, as well any approximations you made.

Transfer task

Consider a tree in which sap flows through each 100 μm-
diamet ... m^3/s
(equal ... nding to
an aver ... re in the
roots i ... ne
pressure at the top of a 30 m tall xylem in the trunk?

Students must Identify and justify choice of model (viscous/nonviscous) from physical situation described in problem

Please briefly explain the reasoning you used to find your answer, ***including how you decided which equations to use, as well any approximations you made.***

Transfer task

In trees, water is c
the flow of sap thr
xylem. A typical xy

Physical clue to use viscous model (dimensions also provided)

trunk of the tree, they extend close to the full height of the tree, which is commonly as great as 30 meters tall. These extremely narrow, long tubes contain a continuous column of water which can then flow into the leaves. Evaporation of water from the leaves (called transpiration) causes water to be steadily drawn up. The leaf structure allows the pressure of water in the xylem to not necessarily be the same as atmospheric pressure.

Transfer task

Viscosity of water mentioned in earlier task instructions (not in problem itself)

The last page gives equations and values of useful parameters such as the density and viscosity of water.

Transfer task

The last page gives equations and values of useful parameters such as the density and viscosity of water.

Equation list gives nonviscous flow equation (Bernoulli) and viscous flow through horizontal cylindrical pipe (Hagen-Poiseuille).

For fully correct analysis, students must *combine* effects of gravity and viscosity.

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
- Simple model implementation, units and calculation

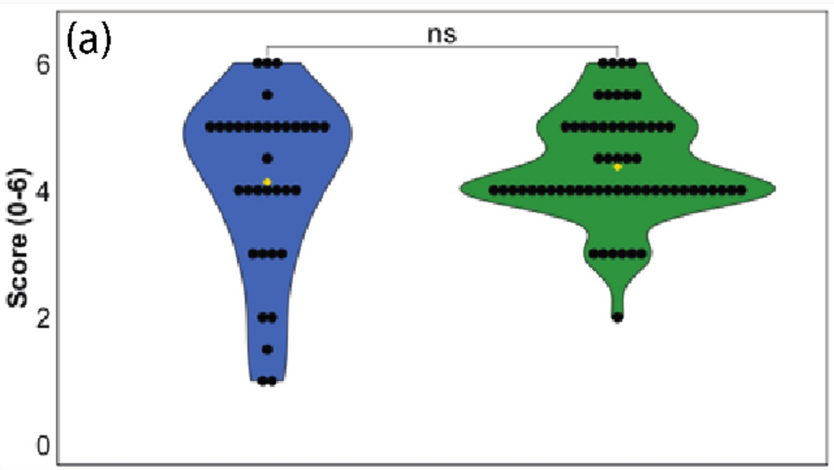
Inter-rater reliability: 0.94

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)

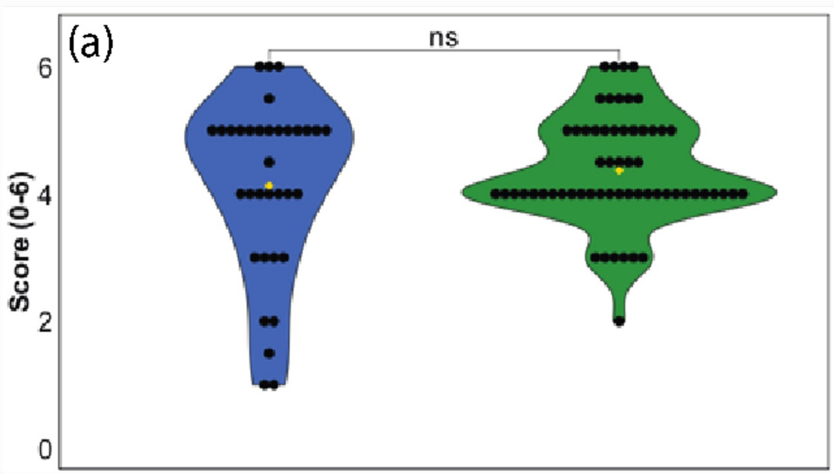
IPLS (N = 61)

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

Both groups implement simple models with comparable success

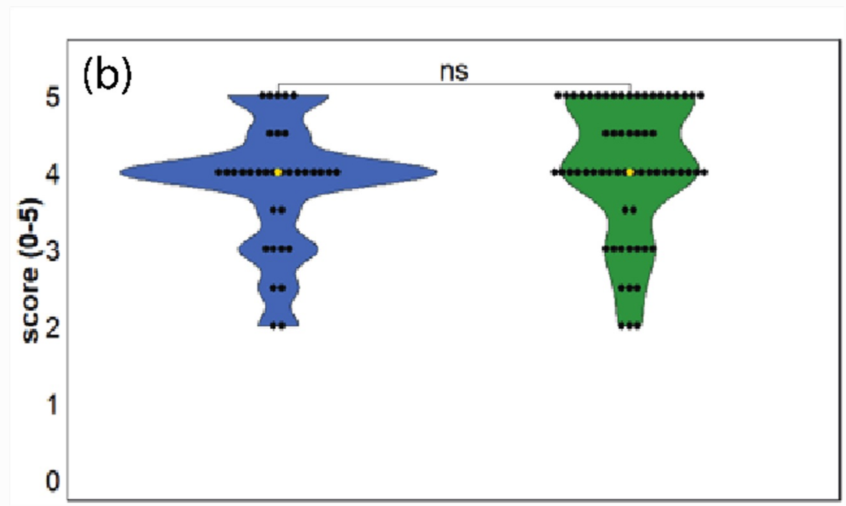
Nikhil Tignor '24 Rain White'24 Brandon Daniel-Morales '24

Standard fluid statics problem



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

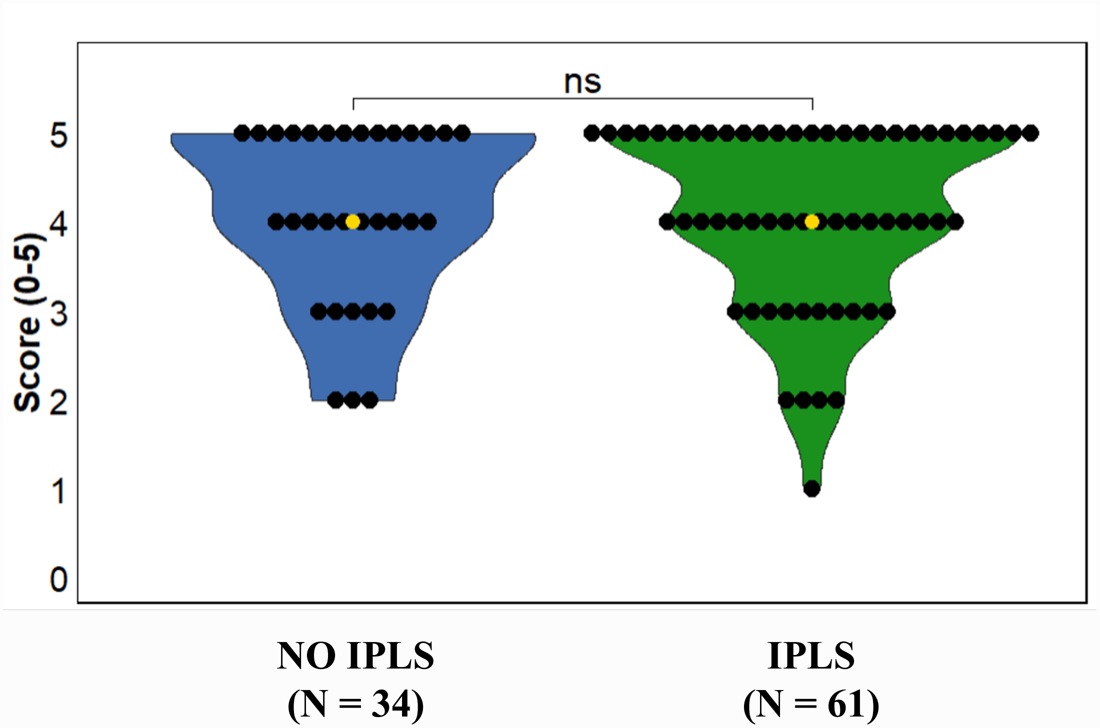
Standard thermodynamics problem



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

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

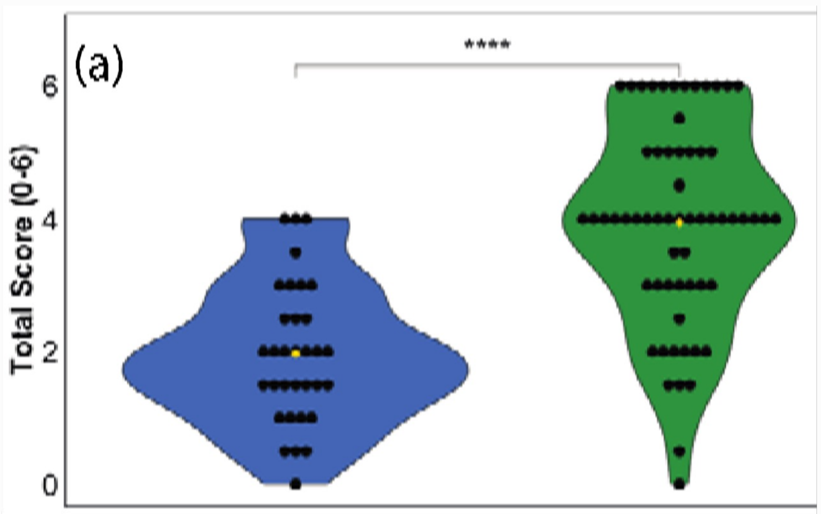
Both groups display comparable calculation/numerical skill



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

BUT IPLS students were significantly more successful at combining models flexibly and justifying them

Total score on modeling parts



NO IPLS (N = 34)

IPLS (N = 61)

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

Take-homes: modeling skill

- IPLS students and standard mechanics students were equally successful at implementing simple models and calculations
- IPLS students were *significantly more successful* in flexibly combining and justifying models to analyze an unfamiliar biological situation
- In other work, we also found that skills endure and interest, relevance, and overall attitudes to physics improve

Thanks to …

NSF 1710875, 2142074

Living Physics Portal: www.livingphysicsportal.org

NSF, HHMI, and Mellon grants

Eugenia Etkina (end of semester task)

Disciplinary experts:

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

Juan Burciaga and session organizers