Explanatory coherence in an introductory physics for life scientists course

Benjamin D. Geller[1], Benjamin W. Dreyfus[1], Julia Gouvea[1,3], Vashti Sawtelle[1], Chandra Turpen[1,2], and Edward F. Redish[1]

[1]Department of Physics, University of Maryland, College Park

[2]College of Computer, Mathematical, and Natural Sciences, University of Maryland, College Park

[3]School of Education, University of California, Davis

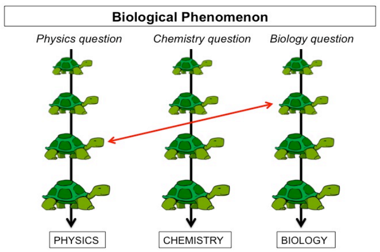
NEXUS/Physics: Crossing Disciplinary Silos

Life science students encounter **disciplinary "silos"** as they navigate the undergraduate science curriculum. These silos promote a disconnected understanding of biological phenomena, with students often developing a fragmented view in which physics contributes little to their appreciation of the natural world [1]. NEXUS/Physics [2] offers a variety of opportunities for life science students to see different disciplinary explanations as meaningfully related:

(1) By identifying physical interactions underlying biochemical heuristics

(2) By connecting disciplinary ideas through the mathematical expression for free energy

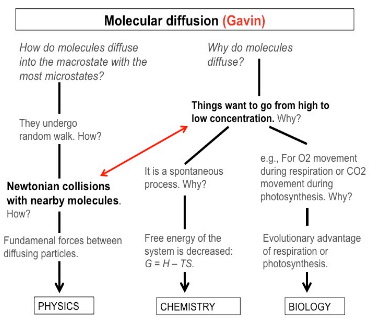
(3) By relating functional biological explanations (the evolutionary "why") to physical mechanism (the "how")



Explanatory silos. Answered questions become new claims in need of justification as one moves downward within an explanatory silo. Turtles are used in reference to the "turtles all the way down" expression of the infinite regress [3]. The red arrows crossing disciplinary silos represent interdisciplinary connections made by students in NEXUS/Physics. These interdisciplinary connections, like vines wrapped around parallel pillars, serve to strengthen one's overall understanding of a phenomenon. The connections form an "interdisciplinary explanatory fabric" in which one's ideas from biology and chemistry are entangled with one's ideas from physics.

Gavin: Physical Interactions Underlying Biochemical Heuristics

… And I think diffusion was when everything started to click; when we talked about how molecules go from higher concentration to lower concentration because they're bumping into each other so much, and so these Newtonian interactions were able to move particles away from one another… there was less collisions and stuff like that… And so I felt like that's when things started to click [*snaps fingers*]… **I was like <u>that's</u> why molecules go from higher concentration to lower concentration… I knew that it happened but then I was like how the hell do they know where the lower concentration is?!** (Interview, 5/31/13)



Gavin describes his frustration with biology or chemistry courses that do not unpack heuristic explanations.

… And in biology we never explain that [*brushes arm across his chest*]. And I think that biology has done obviously very brilliant things and I love biology, but as far as the professors, they're very knowledgeable but they have to go over so much stuff that they don't really take time to explain why things happen. **And I'm a very "why" kind of person; I want to understand why does this happen**. (Interview, 5/31/13)

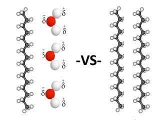
… And his satisfaction in identifying the relevant physical interactions in NEXUS/Physics

… It's because they collide less often when they're further apart than when they're together. And they are going to want the least colliding orientation which is going have the most microstates which is therefore going to have the greatest entropy… **That was very satisfying…** understanding the why really gave me the confidence in order to go into tests and be able to rationalize why things work the way they do and what to look for. (Interview, 5/31/13)

Elena: Connecting disciplinary ideas through the mathematical expression for Gibbs free energy

Students completed a 2-week recitation examining the energetic and entropic contributions to the spontaneous separation of oil and water, and to the spontaneous formation of lipid bilayer cell membranes.

The electrostatic interaction between a polar and a non-polar molecule is stronger than that between two non-polar molecules.



Stronger Electrostatic Interaction

Weaker Electrostatic Interaction

But solubility is determined by considering **free energy**, not just electrostatic energetics [2]:

$$\Delta G = \Delta H - T\Delta S$$

Sign of the free energy change determines solubility

Enthalpy term contains electrostatic energetics

Entropy bridges energy and free energy

Water molecules have more degrees of freedom when not bound to oil molecules, so **the system's entropy is greatest when oil is clumped and water-oil interactions are minimized**. The entropic effect dominates, and (non-polar) oil does not dissolve in (polar) water.

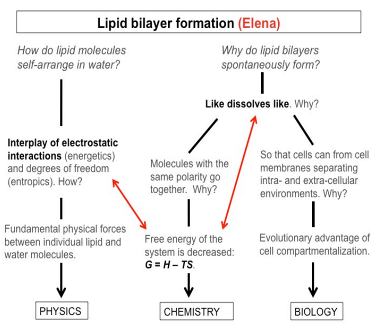
Elena, struggled to find a bridge to **reconcile** her **electrostatic** knowledge **with free energy** being lowered when oil and water separate

… Now this is where **I kind of have two separate thoughts.** Here [points toward a page showing a polar molecule interacting with a non-polar molecule] we are talking about like **electrostatic interactions**… [but] I just don't feel like they're involved in there [pointing to the equation ***ΔG = ΔH – TΔS***] at all! So that's why I'm kind of **having trouble like piecing the two together** in my mind…. (Interview, 2/27/13)

But… when asked to unpack the Gibbs free energy equation, Elena **does uncover** the electrostatic energetics buried inside. She then sees how free energy can be lowered when oil and water separate even if the energetics were to suggest otherwise:

… Well, ok… so **you have bonds and you're breaking bonds** and reforming them… so actually I guess the interactions [that determine *ΔH*], they're **electrostatic** interactions… so now it makes sense. (Interview, 2/27/13)

…[It would make sense] because you would have a positive *ΔH* here [for oil and water separating], but as long as the entropy was higher… and kind of overwhelms this [points to *ΔH* term], as long as it wasn't too much of a [positive *ΔH*], **you would still have a negative *ΔG*…** (Interview, 2/27/13)



Hollis: Coordinating the "how" with the "why"

After a 2-week recitation exploring the energetic and entropic contributions to lipid bilayer formation, students were asked to explain **why lipids self-arrange into bilayers rather than monolayers**:

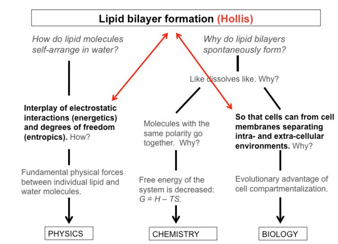
[1] Hollis: I mean, **in terms of biology and biochemistry, the reason why it forms a bilayer is because polar molecules *need* to get from the outside to the inside (of the cell), so you *need* a polar environment inside the cell. But I don't know how that makes sense in terms of physics…**

With Cindy's help, Hollis becomes satisfied that the explanation they have been working together to construct is in fact consistent with her expectation from biology:

[2] Cindy: So what I'm saying is… if (the hydrocarbon tail) is hydrophobic and interacting with water, then it's going to create a positive Gibb's free energy, so it won't be spontaneous. So, in this (monolayer) case you have the hydrophobic tails interacting with whatever's on the inside of the cell, which is mostly water, right?
[3] Hollis: Or other polar molecules.
[4] Cindy: Yeah, other polar molecules… and that's bad.
[5] Hollis: And that's why...OK.
[6] Cindy: That's a positive Gibb's free energy.
[7] Hollis: Yes. See, you explained it perfectly!

After writing for a few moments, Hollis reaffirms her satisfaction in having arrived at a "physics" explanation alongside her "biology" explanation:

[8] Hollis: So that made perfect sense, the way you said it.
[9] Cindy: OK.
[10] Hollis: Because I was thinking that, **but I *wasn't thinking it in terms of physics.* And you said it in terms of physics, so, it *matched with biology*** [fist pump].



Conclusion

Students in NEXUS/Physics describe satisfaction in crossing disciplinary boundaries when making sense of biological phenomena:

- For Gavin, this involved unpacking the **heuristic** that particles move from high to low concentration **in terms of the underlying molecular collisions**.
- For Elena, this involved locating her understanding of electrostatics **within the mathematical expression for free energy**.
- For Hollis, analysis of the energetic and entropic contributions to free energy (and therefore spontaneity) supplemented her **functional understanding** of bilayer formation.

References

[1] J. Watkins, J. E. Coffey, E. F. Redish, and T. J. Cooke, *Phys. Rev. ST Phys. Educ. Res.*, Vol. 8 (Apr 2012).
[2] Redish, et al., *Am. J. Phys.* **82**:5 (2014) 368-377. See also nexusphysics.umd.edu
[3] The origins of the turtle metaphor are uncertain, but it was popularized in Stephen Hawking's "A Brief History of Time" (1988).

Acknowledgments

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Contact: geller@umd.edu