"Like Dissolves Like": Unpacking Student Reasoning About Thermodynamic Heuristics

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Abstract: In our Introductory Physics for Life Scientists (IPLS) course at the University of Maryland, we are building interdisciplinary bridges that help students better understand thermodynamics. One aspect of this endeavor involves having students grapple with the physical processes underlying heuristic rules that they bring to our course from their biology and chemistry classes. In particular, we have implemented a series of activities and problems intended to unpack the hydrophobicity of oil, a key step in understanding the formation of cell membranes. The spontaneous separation of oil and water is predicted by the common rule of thumb, "like dissolves like," but understanding where this comes from requires careful consideration of energetic and entropic effects. The rule must also be reconciled with the seemingly contradictory physical principle that opposite electric charges attract. This paper describes how holding up a heuristic that students have encountered in their biology and chemistry courses alongside physical principles can prompt students to look for interdisciplinary reconciliation among concepts that they previously did not even see as related. We view this as an important step toward a less fragmented experience for science students.

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INTRODUCTION

Scientists employ a range of heuristic devices, or mental shortcuts, that can make problem solving easier or more efficient. For example, "rules of thumb" are informal principles that can be used to predict outcomes of natural processes, but are not strictly or universally accurate [1]. The phrase "like dissolves like" is one such rule of thumb that refers to the idea that solutes will dissolve in solvents only when both solute and solvent molecules exhibit similar chemical polarities [2]. Polar compounds and ionic compounds like table salt dissolve in polar substances like water quite easily, while non-polar carbon chains like oil do not. Thus, "like dissolves like" can be used as a heuristic device to predict that oil and water do not mix.

What such rules do not do, and are not designed to do, is to ground phenomenological predictions in mechanistic reasoning or foundational laws of nature. In fact, heuristic rules can sometimes seem to be superficially at odds with more general physical principles. How, for example, does one reconcile "like dissolves like" with the universally accepted principle that *opposite* electrical charges attract?

The phrase "like dissolves like" by itself does not explicate the underlying explanation for *why* it holds, nor does it specify the conditions for *when* it is appropriate to use it as a heuristic device. This can be problematic for science students who encounter heuristics in their science classes but have not had the opportunity to examine where they come from or consider the limitations of their application.

This paper examines how two students, Gavin and Elena, engage in unpacking the "like dissolves like" heuristic rule in the context of an Introductory Physics for Life Scientists (IPLS) course. In reflecting on their understanding of why oil and water do not mix, Elena and Gavin are confronted with conceptual contradictions stemming from the limitations of the "like dissolves like" heuristic rule they encountered in their chemistry and biology classes.

Their struggle demonstrates one way that students' science experiences can be fragmented and suggests a possible way forward. In designing our course we have developed a novel approach to interdisciplinarity that focuses on providing opportunities for students to explicitly consider the relationships between ideas encountered in different sciences courses — a process we refer to as interdisciplinary reconciliation [3]. We argue that juxtaposing heuristics with physical principles is a particularly effective way to promote interdisciplinary reconciliation in IPLS courses.

Rather than dismissing the heuristic rule as wrong, when *both* the heuristic and the physical principle are taken seriously in a single activity, students can explore how the appropriate level of explanation depends on the particular question being asked. We argue that a

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coherent experience for life science students requires reconciling these different levels of explanation.

METHODOLOGY

We draw on case study interviews in which students reflected on two small group problem solving tasks completed in two 50-minute class sessions several weeks prior, as well as their response to a related quiz question. The first task asked students to carefully examine why it is that oil and water do not spontaneously mix. The second task built on the first to explore the formation of lipid bilayer cell membranes.

The intention of these tasks was to help students better understand the relative roles of entropy and electrostatics in driving the separation of oil and water. Although the electrostatic interaction between a water molecule and an oil molecule may be stronger than the electrostatic interaction between two oil molecules, the water molecules have more degrees of freedom when not bound to oil molecules, contributing to an overall increase in the system's entropy when oil is clumped and water-oil interactions are minimized. Thus, the entropic effect "wins" and, as the rule of thumb suggests, (non-polar) oil does not dissolve in (polar) water. The task introduces students to free energy — the quantity that takes both the energetic and entropic effects into consideration [4]. The lowest free energy state is the one in which oil and water are separate.

The following multiple choice multiple response quiz question was given in class following completion of the two activities:

When non-polar hydrocarbons like oil are placed in water, they tend to bunch together. Which of the following are reasons for this?

A. A non-polar hydrocarbon is more attracted to another non-polar hydrocarbon than it is to water.
B. The entropy of non-polar hydrocarbons is greater when bunched together than when dispersed throughout the water.
C. The entropy of the water is greater when hydrocarbons are bunched than when the hydrocarbons are dispersed throughout.
D. The free energy is lower when the hydrocarbons are bunched together than when they are dispersed throughout the water.

The correct answers were intended to be C and D.

The focus of this paper is *not* on the correctness of students' responses to either the group problem-solving prompts or the above quiz question. Rather, our approach was to use the quiz question and group task to stimulate students' ideas about the relationships between energy, entropy, and free energy in focal interviews.

We interviewed 6 of the 24 students in the course about this task, and our focus in this paper is on two of these: Elena and Gavin. We chose to focus on these two students because both demonstrated (1) nuanced conceptual resources for thinking about the electrostatics of chemical bonding (as will be demonstrated through quotes later in the paper), and (2) knowledge of the "like dissolves like" rule.

We make no quantitative claims about the generality of these two students' responses. Rather, our aim is to describe how our task and the interview prompts that followed the task provided space for interdisciplinary reconciliation, and how Elena and Gavin saw the task as an important link in connecting their physics, biology, and chemistry experiences.

THE CONTRADICTION BETWEEN A HEURISTIC RULE AND A GENERAL PRINCIPLE

Gavin chose Choice A, "a non-polar hydrocarbon is more attracted to another non-polar hydrocarbon than it is to water," as one of his responses to the quiz question. When asked to describe the reasoning behind this selection, Gavin appealed to the heuristic rule he had been "told", but also quickly noted his dissatisfaction with such explanations:

> *I feel like it was just something that we've been told since the beginning of our college careers…we were always told that opposites in electricity attract and likes attract when you're talking about polarities… and the thing is… I don't think anyone in my class actually knows why that is specifically. I think we just know that we've always been told they go together. So we skip the whole intermediate 'how it happens' and jump to the conclusion: well, that [hydrocarbon] has to go to that [hydrocarbon]. But my overall understanding of why that is is pretty weak.*

Despite Gavin's self-assessment, his understanding of how polar and non-polar molecules interact is not weak at all. When asked to compare the strength of the electrostatic interaction between two non-polar molecules to that of the interaction between a non-polar and a polar molecule, Gavin was able to reason through why the latter interaction should in fact be stronger. In describing the dipole/induced-dipole interaction of a water molecule with a hydrocarbon chain, for instance, Gavin stated:

> *These hydrogens coming off [of the hydrocarbon chain] are going to have a balance of charge with the carbon that's right there [on the chain], but then you have this [draws electron pairs on the oxygens on the water molecules], and so even*

though you have a relatively stable structure… you have all these weak interactions [draws dotted lines between the water oxygens and the hydrocarbon hydrogens, indicating hydrogen bonding] that would form if they were close enough...[goes on to explain hydrogen bonding in more electrostatic detail]…

In other words, when the question was framed in the interview setting as a two-molecule electrostatic interaction problem, Gavin quite successfully concluded that an oil molecule interacts more strongly with water than it does with another oil molecule.

In answering the quiz question, Gavin claimed to have chosen Choice A because he saw it as following from the heuristic rule that "like dissolves like". We can explain this choice not as a misunderstanding of the underlying electrostatics, but as an uncritical application of the heuristic rule itself. Prior to this interview, it seems unlikely that Gavin was even aware that his conceptual understanding of electrostatics could be seen as contradicting his notions of solubility. It is unlikely that he had ever seen the two conceptual pieces as *needing* reconciliation until asked to unpack the heuristic in an IPLS course.

When asked if the apparent contradiction between "like dissolves like" and his electrostatic explanation bothered him, Gavin responded, "Yes… *now it does*." And later adds, "in my chemistry classes and in my biology classes…I don't remember discussing that." For Gavin, the opportunity to contextualize the "like dissolves like" rule and discuss its underpinnings was notably absent in his other classes.

Serious treatment of a commonly espoused heuristic in his IPLS course prompted Gavin to identify a conflict between his understanding of electrostatics and his commitment to a rule of thumb that had served him well. This problematizing of the heuristic can itself be seen as an important step towards developing more coherence across different science courses.

RECONCILING ELECTROSTATICS AND THERMODYNAMICS

All else being equal, the electrostatic interaction between a polar and a non-polar molecule is indeed stronger than the electrostatic interaction between two non-polar molecules. As a result, electrostatic energy is lower when a non-polar molecule interacts with a polar molecule than it is when it interacts with another non-polar molecule. But this is an energetic effect, and the spontaneity of processes in the natural world is determined *not* by whether the energy is lowered during the process, but rather by whether the *free energy* is lowered. This key distinction, a discussion of which is rarely found in either introductory biology or introductory physics courses, is at the heart of any effort to reconcile the formal principle "opposite electric charges attract" with the informal principle "like dissolves like". The conceptual bridge between energy and free energy is entropy, and when one considers the entropic effects at play in the oil and water example, it becomes clear that the hydrophobic effect that causes oil to bunch up when placed in water is in fact an entropically-driven phenomenon [5].

"Like dissolves like" is a thermodynamic rule of thumb that can be understood in terms of the Gibbs free energy, $G = H - TS$, while "opposite charges attract" is a fundamental electrostatics principle. Since students are not often asked to discuss electrostatics and thermodynamics at the same time, and often not even in the same course, the two ideas are not easily reconciled in practice.

Elena, in trying to reconcile her electrostatic knowledge with the fact that free energy is lowered when oil and water separate, searched for a way of connecting the two realms:

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 $\Delta G = \Delta H - T\Delta S$] at all! So that's why I'm kind of having trouble like piecing the two together in my mind…

In the course of completing and reflecting on the oil and water task, Elena becomes aware that the energetic and free energetic realms are not connected for her like she would like them to be. She struggles to find a place for her energetic knowledge about electrostatic attraction within the context of an equation that she associates with thermodynamic and free energy considerations.

When asked to unpack the Gibbs free energy equation, and in particular the meaning of the ΔH term, Elena actually *does* herself uncover the fact that electrostatic interactions are buried inside:

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.

When she unpacks how the electrostatics of intermolecular interactions determine the value of ΔH, and thereby inform the overall spontaneity signified by the sign of ΔG, Elena proclaims with relief that things have come together for her. She is also then in a position to understand how it is possible for free energy to be lowered when oil and water separate even if the energetics were to suggest otherwise:

…[It would make sense] because you would have a positive ΔH here [for oil and water separating], but as long as the entropy [points to ΔS term on board] 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...

Elena, like Gavin, sees a contradiction between her understanding of electrostatics and what she knows about the insolubility of oil and water. She goes further during the interview, however, using her knowledge of how the Gibbs free energy depends on enthalpic effects to begin the reconciliation process. By situating the electrostatics within the Gibbs free energy expression, she connects for herself two realms that were previously distinct and unrelated.

BENEFITS OF RECONCILIATION

The Gavin and Elena case studies illustrate at least two benefits of providing students with opportunities to reconcile heuristic rules with general principles. First, by seriously taking on the "like dissolves like" heuristic in an IPLS course, Elena and Gavin saw a need for reconciliation where they may not have before. One could imagine that the thermodynamics of Gibbs free energy and the energetics of electrostatic attraction could quite comfortably remain distinct in a student's mind throughout an entire undergraduate career. Only when asked to explain a biological phenomenon like bilayer formation in the context of a physics course did the need to reconcile those two realms rise urgently to the surface for Gavin and Elena. While "like dissolves like" may be a perfectly satisfactory answer to some questions about solubility, bringing the heuristic into contact with electrostatic reasoning makes it clear that it is not *always* sufficient, and that the possibility of reconciliation crosses disciplinary boundaries.

Secondly, Gavin and Elena's view of the natural world actually *does* become at least marginally less fragmented by virtue of their having reasoned more carefully about the "like dissolves like" heuristic. Both students demonstrate that they have the conceptual resources to make sense of electrostatic and thermodynamic phenomena, but they lacked an opportunity to weave these ideas together. Because Gavin was unsure about the signs of ΔH and ΔS for the mixing process, he did not go as far as Elena in resolving the tension that he discovered. Regardless, framing a single task in terms of both the electrostatic and thermodynamic pieces provided *both* Gavin and Elena with an opportunity to consider how the two related. This is an important step towards viewing their biology and physics experiences as more coherent. As we scale up the course to include a larger number of students, it will be important to assess the sort of reconciliation we describe in this paper in a way that does not always necessitate individual student interviews.

IMPLICATIONS FOR INSTRUCTION

Meeting students where they are requires that instructors take seriously the ideas that students carry with them from prior experiences in and out of the classroom [6]. At the University of Maryland, where a year of biology and a semester of chemistry are prerequisites for taking our novel IPLS course [7], meeting our students where they are means taking seriously the heuristic rules that they bring from their biology and chemistry coursework. We do not seek to "explain away" these heuristics, replacing them with more fundamental physical ideas, but rather we seek to provide activities that will facilitate the positioning of these heuristics within a more coherent picture of how disciplinary explanations are related.

We believe that a focus on interdisciplinary reconciliation of the type described in this paper can be a powerful design feature of IPLS courses [8]. We also recognize that the process is inevitably iterative – the views expressed by Gavin, Elena, and the other students we interviewed about the oil and water task inform our view of how students apply heuristic rules in the context of a physics course, and in turn inform our revisions of the learning environment itself.

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