ABSTRACT

Title of Document: EXPLANATORY COHERENCE IN THE CONTEXT OF THE SECOND LAW OF THERMODYNAMICS

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This thesis examines how undergraduate life science students experience interdisciplinary connections between introductory physics, chemistry, and biology – what the connections look like, how we foster them, and the affect that stems from them. It is about the gaps students experience between their introductory biology, chemistry, and physics coursework, and how we can draw upon students' resources for bridging them.

Rather than looking at connections between physics, chemistry, and biology in the abstract, we ground this thesis in the conceptual context of the second law of thermodynamics, a rich domain for interdisciplinary investigation. Near the end of the thesis, we present an interdisciplinary second law curricular thread that leverages the resources our students have for crossing disciplinary boundaries in this context. Our hope is that other instructors will be convinced to embrace a more interdisciplinary treatment of the second law.

The context of our study is NEXUS/Physics, a novel introductory physics course for life science students. We unpack the resources that NEXUS/Physics students have for thinking about entropy and spontaneity. We argue that an approach to the second law that emphasizes the interplay of energy and entropy in determining spontaneity (one that involves a central role for *free energy*) is one that draws on students' resources from biology and chemistry in particularly effective ways.

We identify three ways in which students in NEXUS/Physics have meaningfully crossed disciplinary boundaries in the context of the second law: (1) by unpacking biochemical heuristics in terms of underlying physical interactions, (2) by locating both biochemical and physical concepts within a mathematical bridging expression, and (3) by coordinating functional and mechanistic explanations for the same biological phenomenon. These classes form a basis that spans the space of interdisciplinary connections that we have observed.

In moments when interdisciplinary gaps are bridged, our students sometimes exhibit positive affect. We look at the source of this affect and how it interacts with disciplinary identity and epistemology. In doing so, we hope to suggest ways of inviting life science students to participate in physics and to see physics as a central tool for making sense of the biological world.

EXPLANATORY COHERENCE IN THE CONTEXT OF THE SECOND LAW OF THERMODYNAMICS

By

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Dissertation submitted to the Faculty of the Graduate School of the
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Professor Edward F. Redish, Chair
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Dedication

This thesis is dedicated to all my remarkable teachers, who made the many years in school worthwhile. I can only hope that my own teaching will some day live up to your example.

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This thesis is the result of an extraordinary collaboration. Our NEXUS/Physics team was headed (and sometimes herded) by Joe Redish, my advisor, who took a risk that he did not have to take when he invited me to join his group several years ago. Joe, I am grateful that you were willing to take that risk, and I am even more grateful that you put together such a wonderful group for me to join. I have been a part of enough research groups, and have lived life long enough, to know that collaborative teams like the NEXUS/Physics gang do not come around very often. I know how lucky I am to have been part of this project. I also thank you, Joe, for teaching me the intricacies of "screen poetry," one of the more useful (but seldom discussed) aspects of being a science communicator. Carefully chosen line breaks are now my friends.

Ben Dreyfus – you were a hard act to follow. Thank you for paving the way and showing me the ropes. I could not have asked for a more supportive or insightful partner in crime these past few years. I still do not understand how I have never found a typo in anything you have written. How is that possible, especially given that we so hurriedly wrote the Resource Letter on the Fast Track? It has been an honor to be the Bentropy to your Benergy.

Julia Gouvea, Vashti Sawtelle, and Chandra Turpen: you have been the NEXUS/Physics heartbeat these past few years. Had just one of you been a mentor, I would have been fortunate. To have all three of you was, frankly, an embarrassment of riches. Although it was not in the formal job description for any of you, you each put mentoring at the top of your busy to-do lists time and again. On many occasions, you put your own research interests on hold in order to make sure that my work received sufficient and timely attention. You instilled confidence by telling me that my ideas were important and exciting, when I was often unsure of that myself, and you made me feel that it was alright for there to be deeply held values underlying my claims. You were amazing listeners and leaders, positioning yourself in such a way that I always felt valued and accepted. I cannot count the times that you helped me turn an inarticulate, clumsy utterance into something that was meaningful and actionable. If more scientists were as poised and articulate and just downright competent as the three of you, the scientific community would be a happier and more productive one. I will carry each of you around with me as models of what it means to mentor, and I will always try as best I can to treat colleagues and students as you have treated me these past few years.

Beyond the NEXUS/Physics team, the Maryland PER and Science Education groups (past and present) pushed me to sharpen my ideas and strengthen my arguments. They listened to my half-formed ideas and helped me to craft them into something better. Todd Cooke, Brian Danielak, Renee Michelle Goertzen (along with Ada and Phi, my smallest and furriest supporters), Ayush Gupta, Kristi Hall, Deborah Hemingway, Mike Hull, Lama Jaber, Vijay Kaul, Eric Kuo, Kim Moore, Alice Olmstead, Gina Quan, Jen Richards, Rachel Scherr, Stephen Secules, Katey Shirey, Tiffany Sikorski, and Erin Sohr were wonderful officemates, colleagues, and constructive critics.

My dissertation committee – Karen Carleton, Andy Elby, Wolfgang Losert, Joe Redish, and Chandra Turpen – asked insightful questions and provided invaluable feedback at several stages of this process. Their input improved this thesis in many ways, both large and small, and I am grateful for their willingness to read more about interdisciplinary reasoning than I am sure they ever hoped they would.

I owe much to the NEXUS/Physics students themselves. I could not have done this work without their insights and willingness to share those insights with our research team. The students' ideas are the intellectual fodder for this thesis.

Catherine Crouch at Swarthmore College was a constant source of encouragement and productive suggestions these past few years, and, perhaps most importantly, gave me something exciting to look forward to beyond the finish line.

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The many friends who have accompanied me on this journey – my Woolsey Street family (including Coops, our frequent guest), my longest and closest friends from the place to which I am now returning (the Swattie road trip crew), and the many others who I have not mentioned – were a steady source of support and much-needed respite from the academic grind.

My identity and everything I value has its roots in home and family. Both of my parents are only children, New York City kids who set out many decades ago to find a new home. They found one, perhaps surprisingly to some, in the rolling cornfields of Chambersburg, PA. I have no aunts, no uncles, and no first cousins. Instead, I grew up with my Chambersburg family. I figured out what I valued when I was counting nickels and dimes at the Legal Services Book Sale, feeding ducks on the Conococheague, and riding my tricycle around the teardrop driveway on Bikle Road. I have lived in many places, and probably have a few more stops ahead of me, but Chambersburg will always be home, and the Chambersburg family will always be my family. Esther and Harry, Cesi and Joe, Lea and Al, Mary, David, Beth, and Cole – you fostered my curiosity, made me feel that I could make a difference in the world, and modeled for me what it looks like to be compassionate and giving. I am so grateful to all of you.

Minna and Jack, I can still see your eyes dancing with excitement. I know you would be proud, and that knowledge is a wonderful gift. Somewhere, over what he is convinced is a far-too-meager portion, Jack is bragging to the Irishman. And Minna is saving me an extra piece of cake.

And finally, to the four people in this world who mean the most to me – Mom, Dad, Ruth, and Danielle – thank you. Thank you for your love, thank you for your support, and thank you for always telling me I could do this when I so often doubted it myself. Thank you for tolerating the stress and the guilt and the self-centered bubble that graduate school all too often became. It really is quite simple: you are the reason that any of this was possible.

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Chapter 1: Introduction

1.1 Motivation

The most formative moments in my training as a scientist have been those in which I have coordinated ideas from different disciplines into a more coherent picture of the natural world. These moments of interdisciplinary connection have been a source of deep satisfaction, and they have shaped my academic trajectory and research choices. They have defined my scientific worldview, sharpening what E. O. Wilson called "a belief in the unity of the sciences – a conviction, far deeper than a mere working proposition, that the world is orderly and can be explained by a small number of natural laws" (Wilson, 1998).

I want my students to experience similar moments of coherence, and similar feelings of satisfaction. Motivating this thesis is a personal conviction that this can only happen when we provide students with opportunities to form meaningful interdisciplinary connections. Providing these opportunities ought to be a central component of any 21st century undergraduate education in the natural sciences. While the existence of distinct disciplines may persist long into the future (or it might not – disciplinary boundaries are increasingly blurred), success in the modern scientific world requires that one cross disciplinary boundaries frequently and effectively. The future of physics lies in the application of its principles and applied technologies to the biological and biochemical sciences, and the future of biology lies in making our descriptions of the living world more quantitative and mechanistic (Bustamante, 2014).

This thesis examines how undergraduate life science students experience interdisciplinary connections between introductory physics, chemistry, and biology – what the connections look like, how we foster them, and the affect[1] that stems from them. It is about the gaps that students experience between their introductory biology, chemistry, and physics coursework, and how we can draw upon students' resources for bridging them.

The vast majority of students who study introductory physics do not want or intend to become physicists. I consider it educational malpractice to ignore this reality. If we aim to meet our students where they are, if we want to be responsive to our students' experiences, we as introductory physics instructors have an obligation to understand the conceptual and epistemological relationship between physics and the life sciences. In this thesis I hope to contribute in a small way to this understanding.

When I started teaching physics to life science majors many years ago, long before I had heard of the "IPLS" (Introductory Physics for Life Scientists) acronym, I was struck by the degree to which the undergraduate experiences of these students were disjointed. I was frustrated that students were provided with insufficient scaffolding for making connections across the scientific landscape. A moment that is particularly salient to me is one in which a biology student asked me if the "*S*" that I

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[1] Throughout this dissertation, "affect" refers to emotion (either positive or negative) that students exhibit and describe in relation to our course. Sometimes in education literature, the term "affect" is used more broadly to describe a student's *motivation*; we do not intend to invoke this broader meaning.

was describing in the context of Boltzmann's relationship ($S = k \ln W$) had "anything to do with" the "S" that appears in the Gibbs free energy relationship ($G = H - TS$) that he had encountered in his biology and chemistry courses. For this student, entropy as described in his physics course did not in any way resemble entropy as described in his biology and chemistry courses. If we are serious about teaching our life science students that physics is relevant and meaningful, this sort of disconnect is unacceptable.

It is unrealistic to expect students to build coherence between a set of seemingly unrelated courses entirely on their own. Worse yet, we as instructors often erect linguistic and epistemological *barriers* that make it harder for students to connect ideas from one course to the next. We describe cross-cutting concepts like energy and entropy in very different ways in biology, chemistry, and physics, often without ever acknowledging the other ways in which these ideas might be described. We leave large interdisciplinary gaps and all too often expect our students to bridge those gaps on their own.

In recent years, several national calls for educational reform have recognized the increased importance of fostering interdisciplinary learning among life scientists (AAAS, 2011; AAMC/HHMI, 2009; National Research Council (US), 2003). While these reports have pointed to the disciplinary fragmentation of cross-cutting concepts like energy and entropy, and to the need to better integrate physics into the life science curriculum, these studies have not examined the hallmarks of interdisciplinary learning at the boundary of physics and biology in detail.

I came to this project with the knowledge that we do a poor job of fostering interdisciplinary connections for life science students, with a deep belief that life science students crave these interdisciplinary connections and have resources for making them, and with a desire to understand how we can lower the barriers that make life science students' academic experiences so fragmented. Much anecdotal evidence has indicated that physics faculty often view their life science students as uninterested in (or incapable of) making connections between physics and the life sciences. In the following section we examine this hypothesis, and conclude that in fact life science students have deep resources for thinking about the connections between physics, chemistry, and biology. They also have a strong desire to make these connections explicit. The resources for reasoning about interdisciplinarity that we identify in the following section are of a general nature, and we will examine more specific and finer-grained resources in the chapters that follow.

1.2 Students' reasoning about interdisciplinarity[2]

Life science students are interested in and capable of conceptualizing meaningful disciplinary relationships. To illustrate this, we present case-study data of NEXUS/Physics undergraduates describing the relationship between scientific disciplines. Rather than viewing biology, chemistry, and physics as existing in disconnected silos, or as overlapping only in narrow regions of common interest, these students exhibit a range of nuanced views about disciplinary relationships. Some students describe hierarchical arrangements that order the

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[2] The majority of this section has been previously published: Geller et al. (2013).

disciplines by degree of system complexity or by the spatial scale used to examine a particular system. In other instances students want physics embedded in a context that positions its relationship to biology via analogy, or reference the way in which general physical principles like energy conservation or entropy maximization impose constraints on biological systems. We argue that these case studies illustrate the varied resources that students possess for seeking coherence across disciplines, as well as the potential barriers to interdisciplinary learning that such views might create when adopted to the exclusion of others.

A major research goal associated with NEXUS/Physics is to examine the strategies that students bring to bear on problems and concepts that cross disciplinary boundaries. Research on interdisciplinary education has rarely focused on students' resources for seeking coherence across such boundaries. Indeed, it is an open question as to what "good" interdisciplinary reasoning even looks like, and how specific tasks and course messaging might influence the strategies that students employ.

1.2.1 Course setting

We have developed a two-semester introductory physics course for undergraduate biology students at the University of Maryland (Redish, et al., 2014). The course seeks to break down barriers that can lead to the construction of disciplinary "silos," and build coherence among the students' experiences in biology, chemistry and physics courses. Particular emphasis was placed on disciplinary authenticity (Watkins, Coffey, Redish, & Cooke, 2012) and on the construction of common models and languages for describing phenomena related to energy and thermodynamics, topics that cross traditional disciplinary barriers. The course was piloted during the 2011-2012 academic school year, with approximately 20 students enrolled.

In this section, we examine how students in the first iteration of NEXUS/Physics describe the relationship between biology, chemistry, and physics, and how those views might inform further iterations of the course. We identify a number of student resources (Hammer, Elby, Scherr, & Redish, 2005; Hammer, 2000; Hammer, 1996) that have the potential to support coherence seeking across disciplines.[3]

1.2.2 Methodology

To get a sense of how students viewed the integration of biology and physics in the course, six case-study students were each interviewed between one and four times during the first year-long implementation of NEXUS/Physics. All of the students in the course were life science majors or pre-health-care students, and all had completed at least one year of biology, one semester of general chemistry, and one year of calculus. Interview protocols were designed not only to elicit discussion about how the course as a whole was being perceived, but also to promote discussion of specific task and exam content that the students had recently experienced. The interviewers were not course instructors, but did play a role in the development of course curriculum.

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[3] These resources are dynamic and context-dependent, and we do not claim that any particular student consistently reaches for a particular view of how the disciplines are related.

Data from interviews with four of these case-study students are examined in this section. The other two students that we interviewed expressed a general conviction that the discipline were connected to each other (the idea that "everything is related somehow"), but did not articulate a structural relationship between the disciplines in a manner that could be clearly defined. Of the four students whose data is described in this section, Anya[4] and Hollis were enrolled in both semesters of the course, whereas Gregor and Wylie joined at the start of the second semester. While we do not claim that these students are necessarily representative of the class as a whole or the introductory physics population generally, we do see these examples as an indication that students may have varied and nuanced sets of resources for reasoning about the disciplines.

1.2.3 Results

Students exhibited a range of nuanced views about disciplinary relationships during our case-study interviews. Some students described a hierarchical relationship in which disciplines are arranged by the spatial scale used to examine a particular system, or by the perceived complexity or level of abstraction associated with the disciplines. In other instances students describe a desire to see physics embedded in a context that positions its relationship to biology via analogy, seeing the explication of such analogies as a particularly useful step toward an understanding of unfamiliar physics. In still other instances, students reference ways in which general physical principles like energy conservation or entropy maximization impose constraints on biological systems. The hierarchical, analogical, and constraint-based views of disciplinary relationships are not mutually exclusive, nor are they exhaustive of students' views. There is overlap and room for debate as to which category best captures a particular instance of reasoning. Nevertheless, we believe that the general framework does provide a first-order approach to describing resources that students may bring to bear in an interdisciplinary science course.

1.2.3.1 The hierarchical view

Several students describe a hierarchical relationship between the disciplines, often with physics at the bottom, chemistry in the middle, and biology at the top.[5] Anya illustrated this hierarchy in great detail, producing a drawing in which each discipline was represented by a rung on a disciplinary "ladder" (Figure 1.1). In discussing her own depiction, Anya describes the vertical axis of her drawing as representing complexity, with the top level (biology) involving quite complicated systems and the bottom level (physics) representing simplified and often idealized situations.

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[4] All student names in this thesis are pseudonyms.

[5] In Chapter 5, we will revisit this notion of the hierarchical relationship between the disciplines, suggesting an alternative structure from Anya's in which there is a hierarchical structure among explanatory steps within each separate discipline, but not necessarily across disciplines. We do not argue that one or the other structure is "correct," but only that each might be useful for understanding different aspects of students' interdisciplinary reasoning.

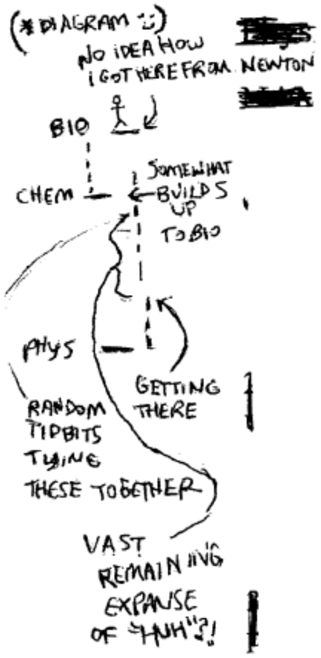

Figure 1.1. Anya's hierarchical depiction of how the disciplines are related. She describes the vertical axis of her drawing as representing complexity, with the top level (biology) involving quite complicated systems and the bottom level (physics) representing simplified and often idealized situations.

For Anya, a persistent struggle in the course stems from attempting to bridge the physics level to the biology level. She feels that the gap between the two disciplines is at times prohibitively large and, unless she is given a justification for doing so, finds it unsatisfying to black box her knowledge about complicated biological systems in order to work with simplified physical models. Anya describes the difficulty she has in trying to "build up" a complicated biological system from what she is learning in our physics course:

> *Physics is like very much just basic everything, and then that builds up to all these particles and all these things you have in chemistry and then you get to biology… everything is just building from this [points to bottom] system after system after system to like really complicated things… So I think that we were just even trying to fill in the gaps here [between bio and chem] that we didn't know. We just jumped to here [points from physics to biology directly]. You don't have all this [waves across the whole spectrum].*

Anya desires more explicit explanations of disciplinary connections between rungs on her ladder. For her, it is desirable to focus on the connections between physics and chemistry first, since she sees this as a necessary preliminary step toward understanding the connections between physics and biology. Far from seeing the disciplines as living in distinct silos, Anya seems convinced that with enough time and effort one could in principle build a coherent framework in which each discipline is described by the discipline below it. She views that process as arduous, however, and later adds that even “expert scientists” might never have sufficient time to fully explicate the details of every connection in the hierarchy.

Gregor also describes the disciplinary relationships in a hierarchical fashion, expressing a belief that “all biology is just chemistry” and “all chemistry is just physics.” Gregor sometimes describes levels on the hierarchy as indicative of the grain size at which a particular discipline focuses its attention (Dreyfus, Sawtelle, Turpen, Gouvea, & Redish, 2014). In Gregor’s view, one discipline is distinguished from another by both the spatial scale at which one examines a particular system, and by the degree to which contextual features can be ignored:

> *Well I mean physics is micro and macro... but physics, yes, like I would say that it does look at things in like a stripped down sense. Not just in the sense that you're zooming physically into small scales physically but… you're talking about vacuums and things that don't exist. You just take out variables and context, whereas in other sciences it's more difficult to do that because you wouldn't see the phenomenon you're trying to investigate.*

Gregor sees complexity as being abstracted away in physics to a degree that is not practical in biology. Later in the interview, Gregor illustrates why he finds it inappropriate to apply the idealization strategies so often utilized in physics to the biological realm:

> *I guess that's just the difference between physics and chemistry and biology. ... Physic[ists] really love to think about things in vacuums, and without context, in a lot of senses. So, you just think about whatever small system you're—isolated system you're looking at, and I guess chemist or biologists thinking about more of an overall context…wherever a reaction or process is happening, that's important to what's going on.*

In discussing the hydrolysis of adenosine triphosphate (ATP), for example, Gregor reconciles his understanding that breaking a chemical bond requires energy with his sense that energy is released during the ATP hydrolysis process as a whole. He believes that physics is more focused on the idealized bond-breaking event, and that this focus fails to capture the complexity of the hydrolysis event in an aqueous biological setting. In Gregor’s view, application of an idealization strategy in physics often masks the very features that are important in biological investigations.

1.2.3.2 The analogical view

For Hollis, a salient feature of interdisciplinary learning is the use of physical analogs to biological systems. In one instance in the course, a biological cell membrane was modeled by a capacitor, both possessing at least superficially similar physical properties. This analogy affords Hollis a way of thinking about capacitors in a familiar context, one that she has studied numerous times before in her biology courses, but it also illustrates some of the limitations of the model:

> *"The capacitor with the two strips - this can be rolled up and modeled like a cell membrane. And I asked [the Professor] a question: 'Would the positive side be like the phospholipid heads? Or the tail?' Like I was confused as to how the capacitor model fits into like a cell membrane. So I mean I guess, it's hard to visualize how it directly translates into a biological system… I'm more familiar with the cell membrane and how a cell works, as opposed to two strips of metal... since I've had more experience, more background about cells, it would be easier for me [using a biological analog] to get a picture that makes sense."*

The capacitor analogy not only allows Hollis to make sense of a capacitor's properties in a way that is more meaningful to her, but it also allows her to more easily question the limits of the analogy itself. Her familiarity with the cell membrane affords her the opportunity to search for ways in which the capacitor model could be extended and the mappings could be made more clear, and in so doing she may actually gain a deeper appreciation for the modeling process generally.

Unlike the hierarchical view, in which one seeks to derive an understanding of biological systems via a series of deductive steps stemming from the underlying physical principles, an analogical presentation allows one to describe particular salient aspects of a biological phenomenon via a more direct mapping. Doing so has the potential to enhance understanding of both systems. The analogical view is by definition one that emphasizes the central role of modeling in the scientific process and, as we see with Hollis, does so in a way that may make the modeling process more accessible.

1.2.3.3 The constraint view

A view of disciplinary relationships that emphasizes the ways in which general physical principles impose constraints on biological systems provides students with another way of connecting physics to biology, and may do so in a way that addresses Anya's concern regarding the large complexity "gap" between the disciplines. Students referred to this constraint-based approach in our interviews. Wylie, for example, sees traditional problems regarding energy conservation as biologically relevant because the same principles would be applied to any system:

> *"Yeah, so there are questions on the MCAT that are just 'this ball is rolling down a hill, you know, what is its KE going to be at the end?' So you know it doesn't put that in a biology context, but it's still a valid physics question... because the reasoning that would have applied to a biological setting would have been very similar to the reasoning applied to a physics problem."*

In this context, Wylie suggests that reasoning strategies involving attention to energy changes would be brought to bear in both the biological and physical problems. The problem of a ball rolling down a hill is still relevant to authentic biological scenarios because the energy conservation principle that one grapples with in solving the problem would constrain any biological system.

In another instance, when discussing the second law of thermodynamics from a perspective of microstate maximization, Hollis becomes puzzled by an example that she sees as violating the second law. She had recently been discussing enzyme-substrate binding in a biology course and, after learning about microstates and entropy in her physics course, concludes that the enzyme-substrate analog binding "would be more entropically favored than normal enzyme-substrate binding." She knows from her biology background that the substrate analog binding process should not be favored, so she begins to search for a way of reconciling the physical principle with what she knows to be true about the biology. Although it turns out that the confusion stems from a misunderstanding of the precise meaning of microstates, Hollis' attempt to impose a physical constraint on her prior biological understanding is a productive instance of using constraint-based reasoning to bridge disciplinary barriers. (Note that the constraint-based view is not necessarily unidirectional. Throughout the course, instances arose in which students attempted to impose biological constraints on physical systems. Often these constraints related to biological "purpose" or "function," as when students would suggest that the protein-transport duties of a cell membrane must be reflected in whatever physics was used to model the membrane.[6])

1.2.4 Discussion

We see evidence in our case-study interviews that students possess a variety of resources for forming connections across disciplinary boundaries. We now turn to discussing some of the affordances and constraints these views have the potential to bring to interdisciplinary reasoning. The hierarchical view that Anya describes makes it natural for her to value deductive, step-wise connections between physics and biology. This view has the potential to support connections among the disciplines in a way that would not be possible if she viewed the disciplines as existing in disconnected silos. At the same time, Anya's hierarchical view also leads to frustration as she recognizes that the full elaboration process could be untenably arduous. She states that even experts might not be able to make all the deductive jumps between physical laws and complicated biological phenomena, and this realization has the potential to discourage her from making similar attempts herself in the short term.

The analogical and constraint-based approaches to disciplinary border crossing suggest an important possibility for addressing Anya's frustration in having to "jump" across what she perceived to be a large conceptual gap between physics and biology. Rather than working to fill in every step in the hierarchical chain, it may well be a more effective strategy to draw upon other resources that students possess for bringing physics and biology into contact. In modeling the cell membrane as a capacitor, for example, Hollis is able to leverage her substantial biological knowledge

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[6] We will return to these biological or functional constraints in Chapter 5.

in a way that makes the capacitor analogy immediately meaningful. While the instructor's intent may have been to introduce the simple capacitor system as a step toward understanding a complicated cell membrane, Hollis' biological knowledge allowed her to work in reverse, as she used her understanding of the biology to map backwards onto her understanding of the physical system. In this way the analogy serves two functions: (1) to bring the physics and biology immediately into contact, without requiring a long deductive chain, and (2) to leverage students' prior knowledge about biology in order to explore the possible connections to a particular physical model.

Likewise, Anya's frustration could be alleviated by examining the biological phenomenon through a lens that emphasizes the role of physical constraints. No matter how complicated the system that Anya seeks to describe, and no matter how unlikely it might be that even experts could make explicit the connections to first principles, the fact that energy must be conserved could have been leveraged as a productive conceptual resource. Constraint-based reasoning, like analogical reasoning, is a resource that allows students to make interdisciplinary connections directly and without the need for extensive deduction. In turn, this allows the instructor to introduce rich biological contexts early on in the course, without the concern that every detail of the biology must first be derived from simple physical laws.

The particular discipline-crossing resources that our students bring to bear is likely dependent on the nature of the problem being investigated and our student's sense of what constitutes a satisfying resolution in that moment. Indeed, most of the students we interviewed refer to more than one of the views mentioned in this section at one time or another during the case studies. Each view of disciplinary relationships comes with its own affordances, but, as was true for Anya, adopting any single one of these views to the exclusion of others can be unsatisfying. Our students are likely to be most productive when they recognize different views of how the disciplines are connected, and can selectively bring to bear those different views at the appropriate moments.

1.3 Conceptual context of the thesis: The second law of thermodynamics

In the previous section, we explored different ways that students seek coherence across disciplinary boundaries. While students may have a conviction that such coherence is possible, in practice it is non-trivial to coordinate disciplinary knowledge across these boundaries. The rest of this thesis takes as its focus the resources that students have for bridging the gaps that exist between disciplinary accounts of biological phenomena. Rather than looking at interdisciplinary connections between physics and biology in the abstract, we ground much of this thesis in the conceptual context of the second law of thermodynamics.

The second law is particularly well-suited for this discussion for two reasons: (1) traditionally the law is taught in strikingly different ways across introductory science courses (see Chapter 4), providing ample opportunity to examine how students bridge disciplinary gaps, and (2) the law (like many thermodynamic laws) is essential for understanding a rich set of biological, chemical, and physical phenomena (see Chapters 5 and 7). Randomness and diffusive processes are of particular importance in biological systems, and a deep understanding of such processes requires a facility with the second law. From the expansion of a gas over space to the spontaneity of chemical reactions to the formation of a cell membrane, the second law of thermodynamics is an indispensable tool for making sense of phenomena in every arena of natural science.

To date, more attention has been paid in the introductory physics education literature to energy and the first law of thermodynamics than to entropy and the second law, and almost none has been paid to free energy (Dreyfus B. , Geller, Meltzer, & Sawtelle, 2014).[7] We argue in Chapter 4 that this is unfortunate. An introductory physics course that emphasizes the first law of thermodynamics but gives short treatment to the second may help students make sense of why only energy-conserving thermal processes are ever observed, but it does not provide students with an opportunity to make sense of why so many more energy-conserving processes are not. There is another motivation for including a robust discussion of entropy and the second law in introductory physics classrooms, whether they are interdisciplinary in nature or not – the second law makes contact with our everyday intuitions about energy in a way that the first law does not. In modern sociopolitical discussions, energy is “wasted” and “used up,” and we worry a great deal about how to “conserve it.” Since the first law of thermodynamics guarantees conservation of energy, students in a course that emphasizes only that law might well perceive a disconnect between energy as discussed in physics classrooms and energy as discussed in their everyday lives (Daane, Vokos, & Scherr, 2014; Daane, Vokos, & Scherr, 2013).

Gibbs free energy is of particular importance in interdisciplinary discussions grounded in the second law, and is a central focus of this thesis. While it may not be made explicit in introductory biology and chemistry classes, associating a negative change in Gibbs free energy with the spontaneity of biological and chemical processes is in fact a restatement of the second law (under constant temperature T and pressure P). So long as temperature and pressure remain constant (as is the case for most biological and chemical processes), the statement that the Gibbs free energy of a system decreases is equivalent to the statement that the entropy of the system plus surroundings increases. This equivalence is at the heart of interdisciplinary reasoning about the second law, and we will return to it often.

1.4. Outline of the thesis

In Chapter 2, we describe the literature that exists on teaching and learning of the second law of thermodynamics across physics, chemistry, and biology, and we discuss the recent literature that addresses interdisciplinary learning at the intersection of physics and biology more generally. We introduce the resources framework that underlies much of the theoretical approach to Chapters 4–7, and point to the literature that has guided our thinking about student affect in Chapter 6. We also review literature related to the nature of disciplinary explanation, since Chapter 5 focuses on the ways in which students in NEXUS/Physics bridge such explanations.

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[7] Dreyfus and Geller are co-first authors and contributed equally to this resource letter.

Chapter 3 lays out the methodology for this study within the context of NEXUS/Physics, the novel introductory physics course for life science students in which this thesis is situated. We discuss the appropriateness of our methods for exploring particular research questions, and for coordinating across these questions. We justify the use of small-*N* qualitative research as an essential tool for understanding interdisciplinary learning, and for identifying the questions for which large-*N* studies may at some point be well suited.

Chapters 4–7 form the substantive core of the thesis. Chapter 4 describes the role that entropy and spontaneity play in NEXUS/Physics, and suggests an approach to the teaching of the second law of thermodynamics that draws effectively on student resources from biology and chemistry. In Chapter 5 we take a broader view, classifying three forms of interdisciplinary boundary crossing in our course. We argue that the three forms comprise a basis that spans the space of interdisciplinary sense making observed over three years of NEXUS/Physics. The examples in Chapter 5 are largely drawn from student reasoning around the second law of thermodynamics, but the classifications apply to interdisciplinary reasoning at the intersection of physics and biology more generally. Chapter 6 looks at the source of affect in interdisciplinary sense making, unpacking a case study episode in which a student experiences positive and negative affect coupled to sources of frustration and satisfying resolution. We view this affect as arising from interaction between the student's identity and disciplinary epistemologies. Chapter 7 describes a second law of thermodynamics curricular thread that we have designed in NEXUS/Physics. We do not use student data to argue for its effectiveness, but suggest that the organization of the thread is well coordinated with student ideas from biology and chemistry.

Chapter 8 synthesizes the results from Chapter 4–7 and discusses both instructional implications and future research directions. In particular, Chapter 8 discusses ontological issues related to free energy, another big idea that needs to be explored at the intersection of interdisciplinary learning and the second law.

Chapter 2: Literature review and theoretical framework[8]

2.1 Interdisciplinarity at the intersection of physics and biology

In recent years, efforts have been made to design introductory physics courses that are specifically tailored to life science students (Meredith & Redish, 2013; Crouch & Heller, 2014; Thompson, Chmielewski, Gaines, Hrycyna, & LaCourse, 2013; Redish, et al., 2014). Many courses, even those not tailored exclusively to life science students, have increasingly emphasized connections to biologically relevant material (Meredith & Bolker, 2012; O'Shea, Terry, & Benenson, 2013; Potter, et al., 2014). These efforts have largely been motivated by a series of national reports calling for reform of the undergraduate life science curriculum. The Bio2010 report on undergraduate biology education (National Research Council (US), 2003) calls for life sciences majors to be better prepared for the coming century by more coherently integrating physics into their training. The *Scientific Foundations for Future Physicians* (AAMC/HHMI, 2009) and *Vision and Change in Undergraduate Biology Education* (AAAS, 2011) reports define scientific competencies for life science students and stress the increasingly interdisciplinary nature of biology. A new version of the Medical College Admissions Test (MCAT) will also focus more specifically on physics that is relevant to life science students (AAMC, 2011).

A number of objectives are routinely cited in these calls for reform to IPLS environments, including the increased importance of physical modeling and quantitative approaches in upper-division biology coursework, the need to train future physicians in methods and technologies developed in the physical sciences, and a general recognition that science disciplines are increasingly integrated and dependent on each other for inspiration and innovation. In this dissertation we also stress the need to help life science students come to "appreciate" or "like" physics. We view this affective result as an end in and of itself.

The recent AAPT Introductory Physics for the Life Sciences (IPLS) national meeting, the recent *American Journal of Physics* and *CBE-Life Science Education* special issues on the intersection of physics and biology, and the recent Gordon Research Conference on research and education at the interface of physics all point toward the rapidly growing commitment to crossing disciplinary boundaries between the physical and life sciences. Sessions devoted specifically to IPLS efforts have been scheduled at national AAPT meetings for the past five years. Redish and Cooke describe the process of negotiation that underlies successful efforts at interdisciplinarity (Redish & Cooke, 2013), and Meredith and Redish describe these growing efforts in terms accessible to a general physics audience (Meredith & Redish, 2013).

In response to these calls for reform, and as evidence of the newfound commitment to better serving our life science students, IPLS courses have been developed at institutions around the country. The common thread through these efforts is a commitment to incorporating new biology-relevant content into the

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[8] Parts of this chapter are published in Dreyfus and Geller et al. (2014), the resource letter on education literature related to the teaching of introductory thermodynamics and statistical mechanics.

introductory physics classroom, although the degree to which these courses take into consideration issues of disciplinary epistemology and attitude varies widely. Some of these efforts have made use of the Force and Motion Conceptual Evaluation (Thornton & Sokoloff, 1998) and Maryland Physics Expectations survey (Redish, Saul, & Steinberg, 1998) in order to begin to assess how different disciplinary perspectives may influence both physics content learning and attitudes toward the subject.

Underlying our approach to IPLS at Maryland has been a commitment to the idea of disciplinary authenticity (Watkins, Coffey, Redish, & Cooke, 2012). Implicit in this view is the understanding that it is insufficient to make only superficial content changes to an introductory physics curriculum when tailoring it to a life science audience. Simply replacing cars with cheetahs in kinematics problems, for example, is an inauthentic approach to interdisciplinarity, while curricular reforms that genuinely draw on students' resources from biology and chemistry are more likely to result in meaningful change.

This dissertation complements and draws upon a host of other efforts made by members of the NEXUS/Physics research group. Gouvea et al. (2013) discuss the iterative nature of interdisciplinary task design, an important feature of our course that is discussed in both Chapters 4 and 7. Sawtelle and Turpen (2014) describe the way in which biology can be leveraged to change a student's relationship with physics, and the analysis of disciplinary affect in Chapter 6 draws on some of the constructs defined in this work. Dreyfus has written extensively on the teaching of energy at the intersection of physics and biology. His papers on chemical energy (Dreyfus, Gouvea, Geller, Sawtelle, Turpen, & Redish, 2014), interdisciplinary reconciliation in the context of ATP hydrolysis (Dreyfus, Sawtelle, Turpen, Gouvea, & Redish, 2014), and ontological issues related to energy in an interdisciplinary setting (Dreyfus B. W., Geller, Gouvea, Sawtelle, Turpen, & Redish, 2014) interact with this dissertation in important ways. In particular, Dreyfus' work on chemical energy and ATP is leveraged in Chapter 5, where we explore forms of interdisciplinary bridging in our course.

2.2. Literature on entropy and the second law

2.2.1 The nature of entropy: language and metaphor

A theme that reappears throughout the discipline-based literature on both energy and entropy education is the role that language – and in particular ontological metaphors – plays in student understanding of thermodynamics. For example, a number of papers address the issue of whether to treat energy as a substance, and the impact that such a choice has on students' conceptual understanding (Dreyfus B. W., Geller, Gouvea, Sawtelle, Turpen, & Redish, 2014; Scherr, Close, McKagan, & Vokos, 2012). Likewise, the literature addresses the many metaphors used to talk about the nature of entropy, examining each one by exploring its use in toy problems and simplified examples (Ogborn, 1986; Duit & Kesidou, 1988; Moore & Schroeder, 1997; Bucy, Thompson, & Mountcastle, 2006; Ben-Naim, 2011). The question of whether the "disorder" metaphor is an appropriate choice, and in what contexts, is one that comes up a number of times in both the chemistry and physics education literature, with several authors suggesting alternatives (Lambert, 1999; Styer, 2000; Jeppsson, 2011; Amin, Jeppsson, Haglund, & Stromdahl, 2012; Jeppsson, Haglund, Amin, & Stromdahl, 2013; Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014). One particular alternative, the idea that entropy is a measure of the "spreading of energy" over available degrees of freedom (Lambert, 2002; Lambert, 2007; Leff, 1996; Leff, 2007; Lambert, 2011), may have value in an interdisciplinary setting where thinking of entropy in terms of its relationship to free energy is important. The precise relationship between entropy and energy spreading is described in a five-part series of articles by Leff (2012). This approach is discussed in the context of the NEXUS/Physics second law curricular thread in Chapter 7. Christensen et al. (2009) describe the tendency of students to view entropy as a conserved quantity, and in Chapter 8 we discuss the possibility that students may have a similar conception of free energy.

Case-study students referenced in this dissertation recall having encountered entropy in a manner consistent with introductory textbook treatments of the topic. The "disorder" metaphor plays a central role in these treatments. In the introductory biology textbook used by our students, for example, entropy is defined simply as "a measure of disorder," with no more precise description or quantitative representation provided (Campbell, et al., 2008). The book notes only that "the more randomly arranged a collection of matter is, the greater its entropy," and that "there is an unstoppable trend toward randomization of the universe as a whole." The introductory chemistry textbook assigned to our students in their general chemistry course introduces entropy in a similar way as the biology textbook, again defining entropy as a measure of disorder in a substance or system (Tro, 2011). When entropy is described qualitatively in the introductory physics text used by students at UMCP who are not enrolled in NEXUS/Physics, it also does so with the familiar refrain that "entropy measures the amount of disorder in a system" (Knight, Jones, & Field, 2007).

A motivation for including a robust discussion of entropy and the second law in introductory physics classrooms is that the second law makes contact with our everyday intuitions about energy in a way that the first law does not. In modern sociopolitical discussions, energy is "wasted" and "used up," and we worry a great deal about how to "conserve it" (Driver, Squires, Rushworth, & Wood-Robinson, 1994). Since the first law of thermodynamics guarantees conservation of energy, students in a course that emphasizes only that law might well perceive a disconnect between energy as discussed in physics classrooms and energy as discussed in their everyday lives (Daane, Vokos, & Scherr, 2014). Effective teaching demands that we leverage students' everyday ideas about the world around them, and the second law is uniquely positioned to help unpack the everyday idea that not all energy is equally useful. Although the amount of total energy in the world does not diminish, the amount of *useful* energy does. This essential distinction is emphasized in literature that relates teaching of the second law to sociopolitical considerations (Daane, Vokos, & Scherr, 2013). Because free energy is central to treatments of the second law in biology and chemistry, this distinction is of particular importance in bridging different disciplinary treatments of the second law.

2.2.2 Disciplinary differences in the second law literature

The physics education literature on entropy primarily addresses student difficulties surrounding heat engines and the Carnot cycle, often adopting an approach to the second law that focuses on efficiency (Cochran & Heron, 2006; Christensen, Meltzer, & Ogilvie, 2009; Smith, Christensen, & Thompson, 2009). As cited above, there are a number of papers in the physics education literature that focus on the role played by language and conceptual metaphors in the construction of ideas about entropy. These papers attend to the benefits and limitations of various entropic metaphors in the context of a number of toy problems and simplified examples. In particular, considerable attention has been paid to the idea of treating entropy in terms of the "spreading" of energy, and to how this approach differs from those that describe entropy in terms of "disorder."

Some physics education literature relating to student understanding of the second law of thermodynamics focuses not on specific curricular or linguistic issues, but on student competency with ideas of probability and statistics that are essential components of any comprehensive treatment of entropy (Mountcastle, Bucy, & Thompson, 2007; Loverude, 2009; Loverude, 2010). This dissertation notwithstanding, there is almost no discussion of how entropy relates to enthalpy and free energy in the physics education literature, nor has then been a focus on student understanding of diffusion and osmosis (Dreyfus B. , Geller, Meltzer, & Sawtelle, 2014). The absence of such literature is one of the motivations for this thesis, and in particular for the discussions in Chapters 4 and 7 of the relationship between free energy and canonical treatments of entropy.

Whereas the physics education literature focuses largely on the relationship of entropy to ideas surrounding reversibility or energy (but not *free* energy), much of the chemistry education literature on entropy focuses on the role that it plays in determining the spontaneity of chemical processes (Craig, 1988; Ribeiro, Costa Pereira, & Maskill, 1990; Ribiero, 1992; Sozbilir, 2003; Sozbilir & Bennett, 2007; Canagaratna, 2008). In particular, the connection between entropy and Gibbs free energy is discussed extensively, as is the degree to which an understanding of entropy aids in an understanding of enthalpy (Carson & Watson, 2002; Sozbilir, 2002; Williamson & Morikawa, 2002; Sozbilir, 2004; Lambert & Leff, 2009). The relationship among these three constructs – entropy, enthalpy, and Gibbs free energy – forms the cornerstone of student understanding of the second law as it relates to chemistry, and of an understanding of chemical equilibria. In the chemistry education literature there is a focus on constant-pressure processes for which enthalpy change is equivalent to heat (Carson & Watson, 1999; Nilsson & Niedderer, 2014), which has the potential to contribute to confusion for students who study thermodynamics in both chemistry and physics environments. There is very little mention of diffusion and osmosis in the chemistry education literature (Dreyfus B. , Geller, Meltzer, & Sawtelle, 2014).

Although the biology education literature does very little to address osmosis and diffusion in a mechanistic way, the literature does describe student understanding of these ideas from a phenomenological perspective (Zuckerman, 1994; Marek, 1994; Vogel, 1994; Odom, 1995; Hebrank, 1997; Odom & Kelly, 2001; Odom & Barrow, 2007). Haddad and Baldo (2010) describe an activity in which students can experience the random motion of diffusing particles, and Fisher et al. (2011) describe the design and validation of an osmosis and diffusion concept assessment. Many papers explore the success or lack thereof of various interventions and pedagogical instruments in improving student mastery of core concepts surrounding diffusion and osmosis (Sanger, Brecheisen, & Hynek, 2001; Meier, Perry, & Stal, 2005). The authors of these papers may or may not themselves view these topics as falling under the "thermodynamics" umbrella, but we mention them owing to their underpinning in statistical physics.

There is very little biology education literature focusing on the second law, either at the micro or macro scale. At least one paper in biology education focuses on the role that student understanding of randomness plays in the development of a coherent conceptual model of the second law (Garvin-Doxas & Klymkowsky, 2008). The absence of a more extensive biology education literature on the subject is striking given the central role that randomness plays in biological systems. There is also very little in the biology education literature about the relationship between entropy, enthalpy, and free energy, despite the biochemical importance of those relationships (Dreyfus B. , Geller, Meltzer, & Sawtelle, 2014). One of the overarching aims of this thesis is to acknowledge these gaps, and to point to life science students' resources for bridging them.

2.3 Theoretical framework

2.3.1 Resources

This dissertation is written against the historical backdrop of constructivism, the theory that students construct new knowledge about the world from their already existing knowledge (Driver, Squires, Rushworth, & Wood-Robinson, 1994). Our focus on student ideas, and the way these student ideas come into interaction, is rooted in a commitment to the constructivist approach. We do not believe that students come to our course with stable, context-independent "misconceptions" (Posner, Strike, Hewson, & Gertzog, 1982; McCloskey, 1983), so we do not see it as our role to confront and replace these misconceptions. Students who are in the process of learning about second law of thermodynamics do not have a single coherent theory, but rather a set of ideas that can be activated differentially in different contexts. At times students may invoke particular ideas in ways that lead them to incorrect conclusions, but the goal of instruction is not to eliminate these ideas entirely.

We want to help students use their disciplinary ideas more productively and to refine their sense of when it will be fruitful to draw on particular sets of intuitions. For example, we do not seek to entirely eliminate student use of the "disorder" metaphor for entropy (see Chapter 4), even if the metaphor is too vague to yield correct predictions in many complicated scenarios. Instead, our goal is to refine student ideas about disorder and build on them to develop a deeper and more coherent framework, one that increases the likelihood that students will leverage the metaphor productively.

In this dissertation we adopt a resources theoretical framework that views students as having dynamic collections of intuitive ideas or "resources" which require further coordination and refinement (Smith, diSessa, & Roschelle, 1994; Hammer, 1996; Hammer, 2000; Hammer, Elby, Scherr, & Redish, 2004; Redish & Hammer, 2009). The term "resources" is used quite broadly in this dissertation. It refers both to phenomenological primitives (diSessa, 1993) and more finely-grained conceptual (Hammer, 1996) and epistemological (Hammer, 1994; Hammer, 2000; Elby, 2001) ideas built from these basic intuitions. Beliefs about the nature of science and about the nature of investigation in particular scientific disciplines are particularly important resources in this dissertation (Hammer, 1994a; Elby, 2001; Hall, 2013), since they help us to understand how best to bridge disciplinary divides.

Task design in our interdisciplinary course is informed by research on how students come to reconcile different ideas about the physical world that they have acquired within and across disciplines. Within a resources framework, reconciliation occurs when students hold multiple (non-contradictory) ideas about phenomena at the same time, and choose which idea(s) to activate or foreground based on the context of a particular phenomenon. In an interdisciplinary setting, this refinement of student intuitions is often informed by particular disciplinary contexts.

A classic example that illustrates intuition refinement involves a task related to Newton's Third Law (Elby, 2001; Redish, 2003), which says that the forces two objects exert on each other are always equal and opposite. Students often have the intuition that a large truck should exert a larger force on a small car than the car does on the truck. Rather than "replace" this idea with a rule to be memorized, students are encouraged to refine their intuition, eventually concluding that the car *accelerates* more than the truck, but also has a smaller mass, so their intuition that the car is affected more is in fact consistent with Newton's Third Law. In this way, students are encouraged not to replace incorrect ideas, but rather to refine intuitions such that they align with correct scientific thinking. In an IPLS context, students bring a set of scientifically productive resources from biology and chemistry and develop a complementary set of resources in physics. Our challenge is to be sure that students develop a deep understanding of the assumptions that underlie both sets of ideas and when and how to use them appropriately.

In designing tasks related to the second law of thermodynamics in our course (in Chapters 4 and 7, in particular), we do not assume that our job is to impart to students a set of canonical rules, nor do we ask students to abandon their initial set of ideas from biology and chemistry. Indeed, our students enter our course with nuanced ideas about free energy and spontaneity, and the challenge is to craft tasks that build on these ideas and refine them. Because we listen to our students and observe how our tasks are taken up in the classroom, problem design in our course is invariably iterative. Student feedback plays an essential role in task design and re-design, and one must be willing to be led in unexpected directions by insightful student ideas.

Our work in Chapters 4, 5, and 6 is grounded in the perspective that students come to our course with disciplinary knowledge that is often fragmented and dynamic. They come to our course with a set of conceptual and epistemological resources that are activated differently in different disciplinary contexts. Our goal is to help students use these resources in productive ways at the appropriate moments. We want to refine our students' sense of why particular resources are particularly useful at particular times. In an interdisciplinary setting, this means drawing on the appropriate resources from biology and chemistry in a physics setting, a difficult endeavor for both novices and experts alike. The resources framework necessarily informs our methodological approach as well, requiring us to look for seeds of productive reasoning in video data, rather than to search for stable misunderstandings

2.3.2 The role of explanation in interdisciplinary learning

Research in science education emphasizes that the construction and understanding of scientific explanations is an important feature of learning science in the disciplines (Braaten & Windschitl, 2011; Craver, 2006; Bechtel & Abrahamsen, 2005). To explain is “to move beyond descriptions of observable natural phenomena into theoretical accounts of how phenomena unfold the way they do” (Braaten & Windschitl, 2011). This definition of explanation distinguishes “what” from “why,” but does not distinguish between different disciplinary “why” questions. For example, it does not distinguish between an evolutionary account of the formation of biological structure and a mechanistic account of how that structure results from the interplay of energetic and entropic effects. While we might conclude that both of these accounts are “explanatory,” they are different enough that our students sometimes struggle to form connections between them. In Chapter 5 we will describe the ways in which students in NEXUS/Physics have bridged these different disciplinary explanations.

Likewise, the role of argumentation in the construction of scientific explanations has been depicted by way of numerous examples within particular disciplines (Kuhn, 2010; Passmore & Svoboda, 2012; Berland & Reiser, 2011; Sandoval & Cam, 2011; Sandoval & Millwood, 2008), but little attention has been paid to the coordination of different disciplinary explanations, or to the ways in which students participate in this coordination. In Chapter 5, we look carefully at the arguments and strategies by which students bridge the explanatory pathways that arise across biology, chemistry, and physics. This bridging work requires that one carefully attend to the way in which explanation, and what counts as satisfactory explanation, is discipline-dependent.

Explanation within a single discipline, let alone across disciplines, is controversial. Philosophers have debated the nature of explanation for decades, with little agreement (Nagel, 1979). Braaten and Windschitl (2011) describe five models of explanation that garnered particular attention in the 20th century philosophy of science literature, pointing out the pedagogical implications of each. One of these models, the “covering law” model, posits that natural events are explained by natural laws that “cover” those events. The Ideal Gas Law, for example, would be said to “cover” the specific ways in which the pressure, volume, and temperature of a gas relate. These covering laws generally provide a mathematical means for representing patterns in the natural world, but do not necessarily do so in a way that is easily adapted to varying contexts.

A number of philosophers have objected to the “covering law” model, arguing that (1) few such laws actually exist, and that (2) the laws express an explanatory commitment that often goes unacknowledged (Cartwright, 1997). Consider, for example, the “like dissolves like” heuristic used to describe the solubility of substances with varying polarity, a heuristic that we will come back to on a number of occasions in this dissertation. The phrase "like dissolves like" does not explain solubility at an atomic or molecular level, but the phrase may still indicate explanatory commitments that are worth exploring, like the relationship between polarity and solubility. If an instructor adheres only to the "covering law" model of explanation, students are not encouraged to engage in reasoning beyond the basic application of the law, nor are they encouraged to explore the context-dependent (often discipline-dependent) nature of different kinds of explanations. As Schwab (1978) puts it, "intelligent and reliable application of principles requires us to have well in hand an understanding of the types of problems to which the principle is applicable and an understanding of the variations in application which are required for problems of different types." This is an idea we will return to in Chapter 5.

The "causal" model of explanation (Salmon, 1978) posits that explanations are most satisfying when they provide causal account. That is, explanations are more satisfying when theories and underlying mechanism are included along with the particular covering law. We will describe examples of this in Chapter 5, and add an additional layer by arguing that explanatory frameworks are especially satisfying when different disciplinary explanations are coordinated. We will describe a student, Gavin, who sees physics as providing a causal account that he did not encounter in his biology and chemistry coursework.

Two other models that have gained traction in the philosophy of science literature – the "pragmatics of explanation" and "explanatory unification view" – are particularly relevant to this thesis. The "pragmatics of explanation" model emphasizes that satisfactory explanation depends on context (Van Fraassen, 1980). As we will see in Chapter 5, different disciplines ask different questions, and those different questions suggest different explanatory pathways. As Schwab (1978) puts it, "different items of scientific knowledge are answers to different kinds of questions and the answer can hardly be said to be understood unless one knows the question to which it is an answer." Our NEXUS/Physics students appreciate that different disciplines approach phenomena in different ways, sometimes explicitly distinguishing a "physics explanation" from a "biology explanation." What counts as a "good" or "complete" explanation depends on the question being asked, and bridging disciplinary treatments of biological phenomena requires carefully distinguishing disciplinary objectives.

Those who posit the "explanatory unification view" (Friedman, 1974; Kitcher, 1989) argue that an essential feature of explanation involves unifying seemingly disconnected phenomena, thereby achieving some degree of global rather than local explanatory power. While this view of coherence motivates much of this thesis, and is most closely aligned with our own view of satisfactory explanation, we argue in the chapters that follow for a broader interpretation of unity.

We argue that unification does not only arise when different phenomena are coordinated within a single model or theory. Unification also arises in the context of a single phenomenon, when different explanations for that phenomenon are coordinated across disciplinary boundaries.

Coherence emerges not only by explaining a lot with a little, but also by connecting multiple explanations into a more integrated framework for understanding phenomena in the natural world.

2.3.3 Disciplinary identity, epistemology, and affect

In Chapter 6 we attend to an instance in which positive and negative affect are coupled to sources of frustration and resolution. The unit of our analysis in that Chapter is not the individual but rather a series of moments in the context of an interview. We do not claim, for example, that the student *always* exhibits these particular emotions for the reasons illustrated by the episode we have chosen. Rather, the episode in Chapter 6 serves to highlight how a student's epistemic resources and ways of positioning his identity were coordinated in these moments. For reasons we describe in Chapter 6, these ways of coordinating epistemology and identity may influence the student in the future.

This framework views neither identity, nor epistemology, nor affect as stable entities that an individual carries with him from moment to moment. Instead, each of these dimensions is influenced by the different contexts in which an individual participates (Gupta, Danielak, & Elby, 2010; Hammer & Elby, 2002; Nasir & Saxe, 2003). This framework does not preclude the possibility that some of these constructs may be more or less consistently activated across a variety of contexts. It simply starts from the assumption that these constructs are sensitive to context and leaves the determination of whether they are more or less stable across context to empirical investigation.

Our focus is on the ways in which an interaction between *identity* and *disciplinary epistemology* is responsible for a student's *disciplinary affect* in an interview about his experiences in this IPLS course. Disciplinary epistemology here refers to ways of knowing and learning associated with a particular discipline (Hammer & Elby, 2003). For students, disciplinary epistemologies are likely to be closely tied to their course experiences (Watkins & Elby, 2013), which may differ . For example, a student might develop an understanding of biology as "complex and difficult to model in a simple way," or of physics as "abstract and idealized" from his biology and physics coursework respectively. Different course experiences could contribute to the development of different sets of epistemological resources. That same student might develop an understanding of biology as describable in terms of elegant mathematical models or physics as uncertain and messy from another set of course experiences. It is also worth noting that students' course experiences may not align with their everyday experiences, and that these differences can have epistemological implications as well (Lising & Elby, 2005).

Identity, like epistemology, is dynamic and context dependent. As Esmonde (2009) puts it, "identities may shift in meaning or salience as one moves from one context to the next." The way a student positions herself relative to a discipline can also vary from moment to moment in more or less consistent ways. A student may over time begin to define herself as "a biology person," but may in other moments feel alienated from or excluded from that discipline (Nasir & Saxe, 2003), particularly in comparison to experts. Another student may identify as "someone for whom physics is really difficult," but may, at times, position herself as more aligned with the discipline (Sawtelle & Turpen, 2014). There may be ways of identifying that are broader than any particular discipline, but that interact with the individual disciplines in influential ways, such as one's view of himself as "a hands-on kind of person" or "a person who is good with symbols."

Epistemology, identity, and affect are related in various and nuanced ways. In Danielak et al. (2014), identity and personal epistemology are coupled such that a student identifies as a certain kind of knower. Disciplinary identity and disciplinary epistemology sometimes evolve together, as when researchers come to position themselves as aligned with or distant from particular disciplinary practices (Osbeck & Nersessian, 2010). Affect, in turn, can stabilize or destabilize epistemic orientations and aspects of identity or may result from a match or mismatch between them. Someone might feel anxious in a context in which his enacted identity is not valued, or proud and confident in a context where it is. At times these constructs of identity, epistemology, and affect reinforce each other, and at times they are in tension. This is particularly true in an interdisciplinary setting in which more than one set of disciplinary identities, epistemologies, and affective responses may be at work.

When defining what it is that we hope our students will learn in interdisciplinary courses, we would be well served to consider also what we hope they might *feel*. We are theoretically committed to the idea that learning interdisciplinary science can be "transformative" (Pugh, 2011), and that affect in such situations is not just a means to an end, but also an end in and of itself. This focus on affect as an end in and of itself, as opposed to a tool or device by which disciplinary learning is enhanced, differs in some respects from other literature that articulates a connection between affect and disciplinary learning (Jaber, 2014).

Chapter 3: Context and methodology

3.1 Context for the study: NEXUS/Physics

The setting for this dissertation is NEXUS/Physics, a novel two-semester introductory physics course offered to life science students at the University of Maryland, College Park. The NEXUS/Physics curriculum emerged from a series of conversations and negotiations between physicists, biophysicists, chemists, biologists, and education researchers at Maryland and elsewhere (Redish, et al., 2014). Although the focus at Maryland was on developing an interdisciplinary physics curriculum, the broader **N**ational **Ex**periment in **U**ndergraduate **S**cience Education (NEXUS) project included other institutions working to develop analogous chemistry and mathematics curricula for life science students (Thompson, Chmielewski, Gaines, Hrycyna, & LaCourse, 2013).

Because a year of introductory biology and a semester of chemistry were prerequisites for the course, NEXUS/Physics could introduce authentic biological problems from the start. In particular, emphasis was placed on energy, fluids, and thermodynamics, and almost every unit in the course included examples situated in an atomic or molecular context. Traditional topics like projectile and rotational motion were de-emphasized, and magnetism was eliminated entirely in order to create space for topics more naturally suited to interdisciplinary exploration. While rotational motion and magnetism have clear biological implications (most importantly in biomechanics and medical technology, respectively), they are not topics that are typically discussed in the introductory biology and chemistry curriculum in any detail. One of our objectives in NEXUS/Physics was to emphasize curriculum that is already explored from different perspectives in biology and chemistry, in order to foster greater coherence with those disciplines. We chose to expand thermal and statistical physics, for example, because of its value in understanding randomness and spontaneity in biochemical processes.

Our curricular choices were continually informed by an ongoing series of conversations and negotiations between physicists, biophysicists, chemists, biologists, and education researchers at Maryland and elsewhere (Redish, et al., 2014). In particular, biologists and chemists that we spoke to argued for an emphasis on fluids, randomness, and thermal physics, and for a de-emphasis on idealized examples of kinematic motion and Newtonian dynamics. A number of our biology and chemistry colleagues saw canonical treatments of 2D projectile motion and blocks on inclined planes as overly simplified “spherical cow” examples that offered no insight into complex biological systems. At the same time, a number of physics colleagues saw these examples as essential contexts in which introductory students learn to manipulate vectors and vector components. Our compromise in this case was to introduce electric force early in the first semester of NEXUS/Physics, and to discuss vectors in the context of Coulomb’s law. Our biology colleagues viewed the electric force as more relevant for solving authentic biological problems than was the gravitational force, so this compromise allowed us to teach important physics competencies in a more authentic biochemical context.

The goal in focusing on biologically relevant topical areas was not just to emphasize the essential role that physics can play in understanding important biological phenomena, but also to enable a classroom environment in which students could be positioned as experts. The goal was for students to view their background in biology and chemistry as relevant and valued, and to draw on students' resources from those disciplines whenever possible. Students were often positioned as valuable sources of biological insight and knowledge, and this insight and knowledge contributed substantively to problem solving in the course.

Data in this thesis were obtained during the first two years of NEXUS/Physics (2011 – 2013), during which time the course was offered to between 20 and 30 students per semester. The students were a mix of sophomores, juniors, and seniors from the various life science disciplines at Maryland, and about half expressed a desire to pursue medical school. Many of the reformed pedagogical features of previous algebra-based physics courses offered at Maryland by Redish and Hammer (2009) were adopted in NEXUS/Physics, but the focus on authentic biological applications was new.

The course involved several weekly components: 3 hours of lecture, 2 hours of laboratory, and 1 hour of recitation. Students completed weekly homework assignments, read online web pages prior to lecture (there was no textbook for the course), and took weekly quizzes. Lectures adopted the "flipped classroom" approach (Crouch, Watkins, Fagen, & Mazur, 2007). Students were responsible for the conceptual material contained in online readings posted before each lecture session. Clicker questions and interactive problem solving and discussion were interspersed with formal presentation by the instructor during class time. The weekly laboratories were transformed between the first and second years of NEXUS/Physics in order to include more biologically relevant activities (Moore, Giannini, & Losert, 2014), and were structured after Scientific Community Laboratories in which students are provided with a minimal protocol and encouraged to explore authentic questions in the manner they deem most appropriate (Kung, 2005).

The weekly recitation sections provided an opportunity for students to work in groups of four on problems that explored rich biological contexts. Each recitation section was facilitated by one Teaching Assistant (TA) and one or more undergraduate Learning Assistants (Otero, Pollock, & Finkelstein, 2010). Many (but not all) of the NEXUS/Physics recitations were designed by the research team in a manner inspired by both the University of Washington Tutorials (McDermott & Shaffer, 2002) and the Open Source Tutorials from the University of Maryland (Elby), with scaffolding provided to encourage open-ended discussion but not necessarily with the intent of arriving at "correct" answers. In our course, recitation sections were one of the best extended opportunities for students to explore the relationship between physical models and biological phenomena. Recitation tasks were designed with specific intent to draw on students' ideas from biology and chemistry, often with the goal of reconciling those ideas with newly learned principles of physics. Recitation tasks related to the second law of thermodynamics are described in the following chapters, and several are attached to this dissertation as appendices.

We view NEXUS/Physics as a well-suited setting in which to explore interdisciplinary connections. The course was framed from the beginning as one that would focus on physics topics most relevant to biology students. There was an explicit recognition that multiple disciplinary epistemologies and multiple disciplinary assumptions exist, and students were frequently provided opportunities to form bridges across them. Students were explicitly asked to describe how energy and entropy were discussed in their prior biology and chemistry courses, for example, and were asked to reflect on the context-specific value of these alternative formulations. Students were encouraged (both in class and on written assignments) to reflect on how their experiences in prior biology and chemistry courses informed their conceptual understanding and epistemological view of physics. For example, students were given an exam essay question asking them to describe situations in which various metaphors for entropy – including those discussed in biology and chemistry courses – were particularly useful. Many exams and homework assignments included at least one essay question asking students to weigh and/or reconcile multiple disciplinary approaches to a particular phenomenon.

NEXUS/Physics also presented a unique opportunity to ground the general exploration of interdisciplinary learning in the particular context of the second law of thermodynamics. Canonical treatments of introductory physics do not typically address random motion, statistical physics, or Gibbs free energy in any detail, if at all (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014). Since these topical areas directly contribute to one's understanding of the second law, this thesis relies on the choice we made to include a robust discussion of the second law and its applications in NEXUS/Physics.

3.2 Coordinating methodological choices with our research questions

Our analytical methodology is guided by the research questions that are central to this dissertation, and by how those questions relate to each other. In this section we list our central research questions, briefly describe the relationships between them, and discuss how our methodological choices are broadly informed by these questions and the relationships between them. Then, in the following sections, we describe why small-*N* qualitative research is appropriate for exploring our questions, and justify the particular analytical lenses that we adopt for answering them.

The central questions that we explore in this thesis are as follows:

1. What general resources do our life science students have for seeing the disciplines (biology, chemistry, and physics) as related? (Chapter 1.2)

2. What specific resources for thinking about the second law of thermodynamics do students bring to our course from prior work in biology and chemistry? (Chapter 4)

3. What broad resources for bridging the gaps between disciplinary treatments of the second law are leveraged by students in our course? (Chapter 5)

4. What are sources of affect in interdisciplinary sense making? (Chapter 6)

These four questions are not independent. Questions 1 and 3 slice our students' ideas about interdiscipinarity in different ways, and in turn suggest slightly different methodological approaches.[9] Chapter 1.2 answers Question 1 by looking at student ideas about how biology, chemistry, and physics are related in a general sense. The interview prompts used in Chapter 1.2 (e.g., "Do you see physics as relevant for biology?") were designed to illicit discipline-level responses. On the other hand, Chapter 5 answers Question 3 largely by looking at the practices and reasoning strategies of students engaged in specific problem-solving tasks (e.g., by examining how students reason about free energy in the context of a second law recitation activity, or when revisiting that activity in an interview).

Where Question 2 asks how our students reason about the second law at the *beginning* of the second law unit in our course (based on prior work in biology and chemistry), Question 3 asks about the disciplinary gap-bridging resources demonstrated by our students over the entirety of their experience in NEXUS/Physics. This distinction, too, has methodological implications. The work in Chapter 5 draws on both (1) interviews conducted throughout the course and (2) video data of students working with each other on small group problem solving tasks throughout the course. We supplemented interview data with classroom data in Chapter 5 for two reasons: (1) in order to broaden the pool of episodes from which we could classify the forms of disciplinary gap-bridging that were prominent in our course, and (2) in order to establish that such boundary crossing occurred within in situ examples of classroom activity. In answering Question 2, on the other hand, Chapter 4 draws primarily on a set of interviews conducted with students prior to any discussion of the second law in our course. Our primary focus in Chapter 4 is on the resources students have for reasoning about the second law by virtue of having been exposed to it in prior biology and chemistry coursework. The initial ideas expressed by the students are then triangulated with an examination of the textbooks that our students use in the biology and chemistry courses that are pre-requisites for NEXUS/Physics.

Since the gap-bridging we examine in Chapter 5 is primarily situated in the conceptual context of the second law of thermodynamics, our discussion of student resources for thinking about this law (in Chapter 4) informs how we answer questions about gap bridging (in Chapter 5). Chapter 5 describes the ways that students bridge different disciplinary resources related to the second law, while Chapter 4 helps us to understand what those different resources are. Put another way, Chapter 4 identifies the starting points from which a number of the bridges in Chapter 5 are built. Many of the connections described in Chapter 5 are connections between ideas surrounding the

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[9] These different ways of slicing our students' ideas about interdiscipinarity are related to each other. For example, we describe in Chapter 1.2 that some students see physical laws as "constraining" biological systems. By analogy, in Chapter 5 we see students use evolutionary advantage as a principle by which biological systems are constrained. So, while Questions 1 and 3 are meant to get at different aspects of students' reasoning about interdisciplinarity, and suggest slightly different methodological approaches, there is a degree of overlap in the answers we found.

second law developed in our course and students' prior ideas about the second law that are described in Chapter 4.

Question 4 asks about the sources of affect in interdisciplinary sense making. In particular, we explore how disciplinary epistemology and disciplinary identity interact to produce affect for one student in one moment in our course. This especially narrow focus differs from our approach to the other three questions, where comparisons across students are helpful in establishing the landscape of student resources. For reasons we will describe below, in answering Question 4 we choose a "middle-ground" approach to analytical grain size. This approach allows us to attend carefully to a particular student's words and the context in which they are said, but does not do so to such an extent that one loses sight of the underlying motivation for asking Question 4.

3.3 Small-N qualitative research

The questions we ask in this dissertation, and the theoretical commitments implicit in those questions, require a qualitative case-study methodology that focuses on the context-dependent reasoning of individuals rather than the coarse-grained, population-level analysis of large-*N* survey data. We did not know whether our students would see biology, chemistry, and physics as related in meaningful ways, nor did we know what those relationships would look like. We did not come to this project already knowing which features of the interdisciplinary learning environment would be used most productively by our students in bridging disciplinary gaps. Had we known the answers to these questions in advance, it might have been possible to poll the class along particular dimensions of interdisciplinary learning that we already knew to be important. This was not the case. Concept inventories focusing on the second law of thermodynamics in an interdisciplinary context did not exist, nor would they have been the appropriate tool for answering many of the disciplinary epistemological questions that we ask about the second law. One of the primary goals in conducting the research described in this dissertation was to identify the right questions for future large-*N* studies to address. Our goal was not to conduct those studies ourselves, as such an investigation would be beyond the scope of this thesis.

In the following chapters we make claims about the *existence* of student resources related to interdisciplinary reasoning in the context of the second law of thermodynamics. We do not claim that *all* students, or even a *typical* student, will draw upon the same resources or coordinate them in the same way. Where it is appropriate, we do point out the ways in which students in NEXUS/Physics are not atypical, since instructors and researchers in different contexts should not view our findings as *necessarily* limited to our particular classroom. In Chapter 4, for example, we supplement student data with an examination of a select number of textbooks that are widely used in introductory biology, chemistry, and physics courses. This examination helps to establish the idea that our NEXUS/Physics students' experiences are unlikely to be unique. Indeed, it is our belief that many of the results in this dissertation will prove to have broader relevance than we are able to demonstrate within the context of a small-*N* study in NEXUS/Physics.

The central claims in this dissertation are *theoretical* claims about the nature and structure of interdisciplinary reasoning in the context of the second law of thermodynamics. These claims are heavily informed by student data collected in the NEXUS/Physics environment. We use student data to provide instantiations of the theoretical claims and to ground the theoretical claims in concrete examples. In most instances, our data is used to demonstrate the feasibility of our theoretical claims rather than their generality – a proof of concept approach that is appropriate for initial forays into research on interdisciplinary student learning. We are careful to limit our conclusions to those that are justified by the small-*N* qualitative methodology we employ, and try not to generalize these results when it is not appropriate to do so. As with any experimentally-motivated theoretical predictions, determining the scope and limitations of the predictions made in this dissertation will require that one test the predictions in a number of contexts beyond the scope of this dissertation.

In Chapter 4, we explore the ways in which ideas surrounding the second law are encountered and articulated by life science students enrolled in NEXUS/Physics. This exploration centers on interviews with students about concepts and problems relating to entropy and spontaneity. Our purpose in these interviews was to better understand the resources that life science students bring to bear in such contexts, and to use this understanding to inform an instructional strategy aimed at a more coherent understanding of the second law. We do not claim from this select number of interviews that all students would talk about entropy and spontaneity in the same way, but we do demonstrate that students *can* productively coordinate these concepts through the construct of Gibbs free energy.

In Chapter 5, a number of episodes were selected because they represent instances in which students make meaningful progress (or describe having made meaningful progress) in interdisciplinary sense making. This progress was most often accompanied by noticeable affect, by a sense of resolution or satisfaction expressed by the students in having bridged a disciplinary divide. Our goal was then to unpack the conceptual and epistemological *sources* of the observed affect, to understand and classify the nature of the interdisciplinary connection that was meaningful to our students. Here again, we do not claim that all students would make interdisciplinary connections in the same way or that all students would be excited by such connections. We do demonstrate that student *can* bridge disciplinary divides in a number of different ways, and that students *can* find these connections satisfying.

In Chapter 6, we examine a single case-study episode in order to identify how disciplinary epistemology and identity *can* interact to produce affect in interdisciplinary environments, but here again we are explicit that not all students would necessarily experience the environment in the same way.

3.4 Choosing an analytical grain size for the exploration of affect

Large-*N* studies that rely solely on survey data are by their nature coarse-grained in their analytical approach. Without observing students in the classroom or speaking with them in an interview setting, it is not possible to attend to the finer-grained dynamics of individual students' or student groups' reasoning. On the other hand, one has to make decisions about just *how* finely grained one's analysis of qualitative student data ought to be in any particular study. It is our view in this dissertation that there is often value in a "middle-ground" approach to analytical grain size. This approach attends carefully to students' words and the context in which they are said, but does not do so to such an extent that one loses sight of the broader goals of the theoretical project and, just as importantly, of the audience that one is trying to reach.

Consider, by way of an illustrative example, how one might go about identifying affect in an educational setting.[10] There is a spectrum of analytical grain sizes with which one might try to investigate students' various affective responses. On the fine-grain-size end of the spectrum, one could use micro-facial expressions, gestures, and subtle variation in vocal inflection to ascertain the emotion being felt or expressed by a student at a particular moment (Scherr, 2008; Chase & Wittman, 2013). This approach may be particularly helpful, for example, in situations where it is important to coordinate emotion with very precise moments in the reasoning process or with very precise features of the educational environment. It would be especially important to do this when one is interested in the moment-to-moment ways in which affect facilitates the disciplinary learning process (Jaber, 2014).

On the coarse-grain-size end of the spectrum, one might simply ask a student to report on any emotion they are feeling or previously felt (either in an interview setting or with a survey), thereby relying on students to accurately and explicitly articulate their affect. It would likely be sufficient to take this approach if one was interested in the presence or absence of affect associated with a long-term experience (like an entire course or a unit in a course), or in the student's personal perception of his or her own affect after the fact. If one were interested in determining the percentage of life science students in a class who report some level of pleasure or satisfaction in doing physics, for example, a course-grained end-of-term survey might be a valuable tool.

We take the view that neither an extremely coarsely-grained approach nor an extremely finely-grained approach is appropriate in the context of our particular discussion of affect in this thesis. The coarse-grain-size approach would not determine how specific conceptual and epistemological stances might be tied to the observed emotion. As we will describe in Chapter 6, there are multiple possible reasons why a life science student in our course might like physics. If we want to understand the source of affect, we need to attend to the context in which students describe their satisfaction.

At the same time, our purpose in discussing affect in this dissertation is not to suggest ways by which affect facilitates learning. Rather, in Chapter 6 we are interested in affect that is an *end result* of disciplinary gap bridging. Our focus is on identifying affect that results from moments of interdisciplinary coherence, not on understanding how that affect subsequently influences student learning. (We do not dispute that there are a number of interesting ways in which the affect we describe might indeed have such influence, but that is not the focus of our argument.)

Our goal in Chapter 6 is to identify apparent "frustration" or "satisfaction" stemming from moments of interdisciplinary coherence. We do so by an approach that relies on a small set of markers that, when coordinated with students' explicit utterances, are sufficient for indicating a particular affective response. When a student in Chapter 5 pumps her fist and expresses the fact that an explanation has just been

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[10] Affect is discussed in Chapter 6, but it is not the primary construct in this thesis. It does serve, however, as a useful dimension through which to describe what we mean by a middle ground analytical approach.

explained “perfectly” by her group mate, for example, we take that as sufficient evidence for claiming that she is “satisfied” in this moment. If we were interested in further exploring how this satisfaction helped her learn physics more successfully or in understanding the degree of her satisfaction, we would likely need to inspect the group dynamics in greater detail.

Our approach is to provide the minimal set of non-verbal markers necessary for supporting the claim that a student’s words have an affective dimension. What counts as sufficient in this regard undoubtedly depends on the audience that one is trying to reach. Several of the chapters in this dissertation are aimed primarily at physics instructors who may be interested in adopting interdisciplinary approaches in their introductory classrooms. Education researchers are not the sole, or even primary audience in these chapters, and we have made purposeful analytical choices with our audience in mind. Eventually it may be commonplace in education research to leverage fMRI technology to determine the conditions under which different parts of a students’ brain are activated, or researchers might collect student saliva in order to test for the presence of particular chemicals or hormones that are associated with particular emotions (Stroud, Salovey, & Epel, 2002). Until that time, and likely even after it, it is our view that the identification of affective responses is at least a partially subjective endeavor. A human being must use his or her judgment to conclude that a particular marker is indicative of a particular emotion. It was our choice in this dissertation to adopt a middle-ground approach, in the hopes of most effectively reaching our intended audience.

3.5 Data collection and analysis

Data in this dissertation were obtained during the first two years of NEXUS/Physics (2011 – 2013), during which time the course was offered to between 20 and 30 students per semester. The course was subsequently scaled up to multiple 120-student lectures during the 2013-2014 academic year, but data from these scaled up classrooms is beyond the scope of this thesis. Our research team (Benjamin Dreyfus, Julia Gouvea, Vashti Sawtelle, Chandra Turpen, and the author) collected extensive data during each of the four semesters of the 2011-2012 and 2012-2013 academic years. The data is used in this dissertation as well as in a number of other papers (Dreyfus B. W., Geller, Gouvea, Sawtelle, Turpen, & Redish, 2014; Dreyfus, Gouvea, Geller, Sawtelle, Turpen, & Redish, 2014; Dreyfus B. , Geller, Meltzer, & Sawtelle, 2014; Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014; Geller, Dreyfus, Sawtelle, Svoboda, Turpen, & Redish, 2013; Gouvea, Sawtelle, Geller, & Turpen, 2013; Sawtelle & Turpen, 2014; Sawtelle, Sikorski, Turpen, & Redish, 2013) and one other dissertation (Dreyfus B. W., 2014). We expect that future research will continue to make use of the data.

Data was collected during each lecture period in multiple ways. Three cameras were used to record classroom activities, one from the back of the room to capture a view of the instructor and class as a whole, and two cameras (with accompanying microphones) directed at student groups to capture particular groups’ discussions. One or more members of the research team was present in each lecture in order to record real-time notes. These notes involved both “play-by-play” documentation of classroom activities and analytical notes about instructor-student or student-student interactions of significance. Many of these notes were classified in real time according to thematic categories that were of particular interest to the research team. For example, "nature of science" or "nature of biology" comments or discussions were tagged as such, while discussions relating to the second law of thermodynamics or interdisciplinary reasoning – of particular importance in this thesis – were given their own categories as well. This real-time cataloging allowed us to more feasibly search for relevant data amongst the hundreds of hours of video that we recorded.

Our research team also recorded two student groups per section for each recitation activity. During the first year (2011–2012), when only one section of the course existed, only two groups were filmed per week. During the second year (2012–2013), when there were two sections of the course, we often recorded four groups per week. After the laboratory component of the course was reformed between the first and second iterations of NEXUS/Physics, we recorded student groups doing the labs. We kept electronic scans of all quizzes, exams, and written homework problems, as well as electronic records of students' responses to assigned readings and online homework tasks.

The research team conducted 48 semi-structured interviews with 23 students during the 2011-2012 and 2012-2013 NEXUS/Physics courses. All students enrolled in the course were asked if they were interested in participating in interviews, and almost all the students who expressed a willingness to participate were interviewed at least once. Some interviews were primarily topical, involving prompts designed to probe student reasoning about particular content areas before and after those areas were covered in class. Other interviews contributed to longitudinal case studies that were designed to examine conceptual, epistemological, or affective changes over time. Almost all the interviews involved questions designed to further explore how students reasoned through recitation tasks or exam problems. Students were also routinely given space in interviews to describe moments in the course that stood out to them as particularly meaningful.

Chapter 4 draws on case-study interviews conducted during the 2012-2013 academic year in order to get a sense for how our students had previously been exposed to entropy, free energy, and spontaneity in their biology and chemistry coursework. We interviewed six students prior to the unit about entropy and the second law of thermodynamics, and again once or twice (depending on the student) after the unit was complete. Our focus in Chapter 4 is on four of these case-study students: Elena, Tammy, Gavin, and Otto (all pseudonyms). We chose to focus on these four students because all of them demonstrated nuanced conceptual resources for thinking about entropy and its relation to free energy and spontaneity. (The other two students had limited exposure to entropy in their prior coursework, although many of their ideas about spontaneity aligned with those of the four students we describe here.) Chapter 4 focuses particularly on interviews with these students *prior* to the unit on entropy, at which point their views had likely been shaped primarily by their experiences in either high school or in biology and chemistry courses at the University of Maryland.

Chapter 5 draws primarily from two sources of student data: small-group interactions from recitation sections during the 2011-2012 academic year, and case-study interviews conducted with students during the 2012-2013 academic year. A select number of episodes were selected for inclusion in Chapter 5 because they represent instances in which students make meaningful progress (or describe having made meaningful progress) in interdisciplinary sense making. This progress was most often accompanied by noticeable affect, by a sense of resolution or satisfaction expressed by the students in having bridged a disciplinary divide. As researchers, this affect served as a useful indicator that the episode was worth exploring in detail.

The research team met weekly to discuss data collection and to analyze clips that were selected by each member according to his or her particular research interests. Beyond discussion of logistical issues, a typical research group meeting would entail spending an hour discussing a relatively short piece of video from either an interview or classroom setting. We discussed how pieces of student data did or did not support a particular theoretical claim, and often these discussions shaped research agendas in important ways. Data was occasionally shared with a wider audience, either in the weekly Physics Education Research Group/Science Education (PERG/Sci.Ed.) research meetings or in the bi-weekly Biology Education Research Group (BERG) meetings.[11]

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[11] More specific analytical approaches than those that have been discussed in this chapter will be reviewed within the body chapters themselves.

Chapter 4: Entropy and spontaneity in an introductory physics course for life science students[12]

4.1 Introduction

4.1.1 Why Entropy?

Countless physical processes that *could* spontaneously occur without violating the conservation of energy principle are never observed. We do not see chairs spontaneously absorb energy from the floor and begin to slide across rooms. We do not see smoke spontaneously coalesce in the corners of smoky bars. And we do not see shivering campers transfer heat to their campfires. None of these processes would violate the first law of thermodynamics, but all of them violate the Second. An introductory physics course that emphasizes the first law of thermodynamics but gives short treatment to the second may help students make sense of why only energy-conserving thermal processes are ever observed, but it does not provide students with an opportunity to make sense of why so many more energy-conserving processes are not. Put another way, the first law of thermodynamics is a necessary but insufficient rule for making sense of the thermal world.

There is another motivation for including a robust discussion of entropy and the second law in introductory physics classrooms – the second law makes contact with our everyday intuitions about energy in a way that the first law does not. In modern sociopolitical discussions, energy is "wasted" and "used up," and we worry a great deal about how to "conserve it" (Driver, Squires, Rushworth, & Wood-Robinson, 1994). Since the first law of thermodynamics guarantees conservation of energy, students in a course that emphasizes only that law might well perceive a disconnect between energy as discussed in physics classrooms and energy as discussed in their everyday lives (Daane, Vokos, & Scherr, 2013). Effective teaching demands that we leverage students' everyday ideas about the world around them, and the second law is uniquely positioned to help unpack the everyday idea that not all energy is equally useful. Although the amount of total energy in the world does not diminish, the amount of *useful* energy does (Daane, Vokos, & Scherr, 2014). Only the second law of thermodynamics accounts for this essential distinction.

4.1.2 Why entropy in an IPLS course?

The case for including entropy in any introductory physics treatment of thermodynamics is strong, but the case is even stronger for including such a treatment in Introductory Physics for Life Science (IPLS) courses. Randomness and diffusive processes are of particular importance in biological systems, and a deep understanding of such processes requires a facility with the second law. Diffusion accounts for the movement of oxygen from the alveoli to the capillaries during respiration, and for the movement of CO_2 within leaves for use in photosynthesis (Nilsson G. E., 2010; Evans & Von Caemerer, 2010). The formation of ordered biological structures in aqueous environments depends on an entropically driven

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[12] This chapter is based on previously published material: Geller et al. (2014)

hydrophobic effect (Chandler, 2005). And an understanding of how directed motion can emerge from random motion is essential for making sense of many directed subcellular processes (Garvin-Doxas & Klymkowsky, 2008).

A second reason for spending considerable time on entropy in an IPLS course is that it provides the link between energy as described in a typical physics course and free energy as described in a typical biology or chemistry course (Levine, 1978). Consider the relationship between the Helmholtz free energy, the internal energy, and the entropy of a system:

$$F = U - TS$$

In biology and chemistry texts, it is often the free energy F (or, as we will see later, the Gibbs free energy G) that plays a central role, as the sign of the change in that quantity determines whether biochemical processes and reactions can occur spontaneously (Levine, 1978). In a typical introductory physics treatment of energy, some time is spent unpacking what goes into the internal energy term U in the above equation. A treatment of electrostatics, in particular, can be viewed through a thermodynamic lens as living inside the internal energy term in the expression for free energy. (Unfortunately, in a typical introductory course, “conservation of energy” and “the first law of thermodynamics” are usually taught separately, and electrostatics is never explicitly connected to thermodynamics. Seeing electrostatics as living inside U requires a layer of interpretation not often apparent to our students.) The link between energy and free energy is entropy, and as the entropy of a system increases, less energy is “free” to do useful work (Levine, 1978).

To make the connections between energy, entropy, and free energy concrete, consider a standard idealized physics problem, the free expansion of a thermally isolated ideal gas (Figure 4.1).

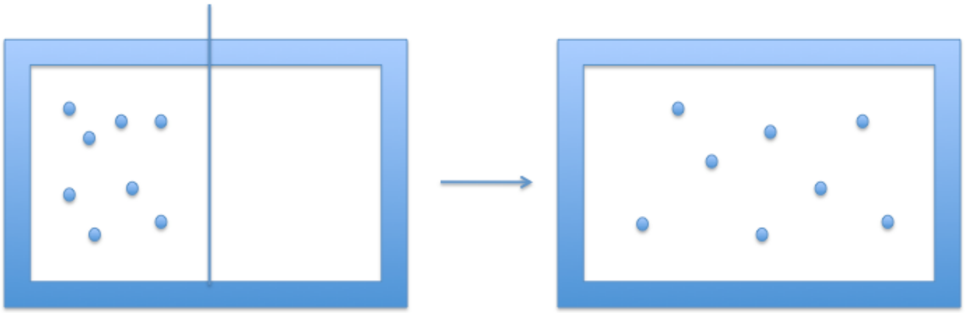


Figure 4.1. Free expansion of a thermally isolated ideal gas. When the barrier is removed, the gas expands to fill the available volume. The *energy* of the gas is constant during this isothermal free expansion, but the *free energy* of the gas decreases.

When the barrier is removed, the gas freely expands to fill the available volume. Since the compartment is thermally isolated from its surroundings, the internal energy U of the gas remains constant during the expansion, while the entropy of the gas increases. The result is that the freely expanded gas has the same energy but less *free* energy than the gas did before the barrier was removed. The expanded gas has less capacity to do work on its surroundings than the compressed gas did, which makes sense if we make the typical association between free energy and the capacity to perform useful work (Levine, 1978).

This chapter argues that thinking of entropy as a link between energy and free energy, and in turn framing a discussion of the second law of thermodynamics in the context of considerations about free energy and spontaneity, can be an important step toward bridging different disciplinary treatments of thermodynamics. The context for this discussion is the NEXUS/Physics course (Thompson, Chmielewski, Gaines, Hrycyna, & LaCourse, 2013; Redish, et al., 2014), an introductory course for life science students that leverages students' experiences in introductory biology and chemistry courses. Meeting our students where they are means building upon the resources for thinking about free energy and spontaneity that IPLS students bring from their experiences in those classes. Many students enrolled in NEXUS/Physics had not previously taken a chemistry course with an *explicit* focus on entropy and free energy. Despite this, our students report having seen these ideas in their introductory biology and chemistry courses, and report having used these ideas in meaningful ways. In light of these reports, we see the discussion in this chapter as relevant to a wide range of IPLS courses, including ones in which students may not yet have had other courses that explore thermodynamics in depth.

4.1.3 Leveraging Student Ideas

Meeting our life science students where they are means leveraging and refining their ideas about free energy and spontaneity rather than attempting to replace them. We adopt a resources theoretical framework that views students as having dynamic collections of intuitive ideas or "resources" which require further coordination and refinement (Hammer, Elby, Scherr, & Redish, 2004; Hammer, 2000; Redish & Hammer, 2009). Students who are in the process of learning about thermodynamics do not have a single coherent theory, but rather a set of ideas or "resources" that can be activated differentially in different contexts. At times students may invoke particular resources in ways that lead them to incorrect conclusions, but the goal of instruction is not to eliminate these resources. We want to help students use these resources more productively and to refine their sense of when it will be fruitful to draw on particular sets of intuitions. For example, we do not seek to entirely eliminate student use of the "disorder" metaphor for entropy, even if the metaphor is too vague to yield correct predictions in many complicated scenarios. Instead, our goal is to refine student ideas about disorder and build on them to develop a deeper and more coherent framework, one that increases the likelihood that students will leverage the metaphor productively.

Task design in our interdisciplinary course is informed by research on how students come to reconcile different ideas about the physical world that they have acquired within and across disciplines. Within a resources framework, reconciliation occurs when students hold multiple ideas about the world at the same time, and choose which idea(s) to activate based on the context of a particular phenomenon. In an interdisciplinary setting, this refinement of student intuitions is often informed by particular disciplinary contexts. A classic example that illustrates intuition refinement involves a task related to Newton's third law (Elby, 2001; Redish, 2003), which says that the forces two objects exert on each other are always equal and opposite. Students often have the intuition that a large truck should exert a larger force on a small car than the car does on the truck. Rather than "replace" this idea with a rule to be memorized, students are encouraged to refine their intuition, eventually concluding that the car *accelerates* more than the truck, but also has a smaller mass, so their intuition that the car is affected more is in fact consistent with Newton's third law. In this way, students are encouraged not to replace incorrect ideas, but rather to refine intuitions such that they align with correct scientific thinking. In an IPLS context, students bring a set of scientifically productive resources from biology and chemistry and develop a complementary set of resources in physics. Our challenge is to be sure that students develop a deep understanding of the assumptions that underlie both sets of ideas and when and how to use them appropriately.

In designing tasks related to the second law of thermodynamics in our course, we do not assume that our job is to impart to students a set of canonical rules, nor do we ask students to abandon their initial set of ideas from biology and chemistry. Indeed, our students enter our course with nuanced ideas about free energy and spontaneity, and the challenge is to craft tasks that build on these ideas and refine them. Because we listen to our students and observe how our tasks are taken up in the classroom, problem design in our course is invariably iterative. Student feedback plays an essential role in task design and re-design, and one must be willing to be led in unexpected directions by insightful student ideas.

4.2 Methodology

Given the importance of the second law of thermodynamics across biology, chemistry, and physics, we set out to explore the ways in which ideas surrounding the second law are encountered and articulated by life science students enrolled in our IPLS course. This exploration involved a survey of several introductory disciplinary textbooks that our students used and, more importantly, interviews with students about concepts and problems relating to entropy and spontaneity. Our purpose in these interviews was to better understand the resources that life science students bring to bear in such contexts, and to use this understanding to help them in developing a more coherent understanding of the second law.

We draw on case-study interviews conducted with students in our NEXUS/Physics course at the University of Maryland, College Park (UMCP) (Thompson, Chmielewski, Gaines, Hrycyna, & LaCourse, 2013; Redish, et al., 2014). Because our course has a year of biology and a semester of chemistry as prerequisites, our assignments and small group problem solving sessions leverage our students' familiarity with the material in those courses by introducing authentic biological problems from the beginning. The second iteration of NEXUS/Physics was offered to 31 students during the 2012-2013 academic year.

In order to get a sense for how our students had previously been exposed to entropy, free energy, and spontaneity, we interviewed six students prior to the unit about entropy and the second law of thermodynamics, and again once or twice (depending on the student) after the unit was complete. Our focus in this chapter is on four of these case-study students: Elena, Tammy, Gavin, and Otto. We chose to focus on these four students because all of them demonstrated nuanced conceptual resources for thinking about entropy and its relation to free energy and spontaneity. (The other two students had had little exposure to entropy in their prior coursework, although many of their ideas about spontaneity aligned with those of the four students we describe here.) We focus in particular on interviews with these students *prior* to the unit on entropy, at which point their views had likely been shaped primarily by their experiences in either high school or in biology and chemistry courses at the University of Maryland.

Although our interviews with these students suggested that their thinking about entropy and related topics had changed as a result of the tasks and problems completed during our second law unit, we do not examine those changes in any detail here. We also make no quantitative claims about the generality of these four students' responses. Instead, we describe how these students' notions about entropy and spontaneity from prior experiences suggest an approach to teaching these topics in an IPLS environment. Our aim is to describe how the ideas expressed by Elena, Tammy, Gavin, and Otto may inform our efforts to make life science students' physics, biology, and chemistry experiences more coherent.

To get a sense for how our case-study students thought about entropy, we showed each of them a series of slides illustrating processes for which entropy plays a significant role (Figure 4.2).

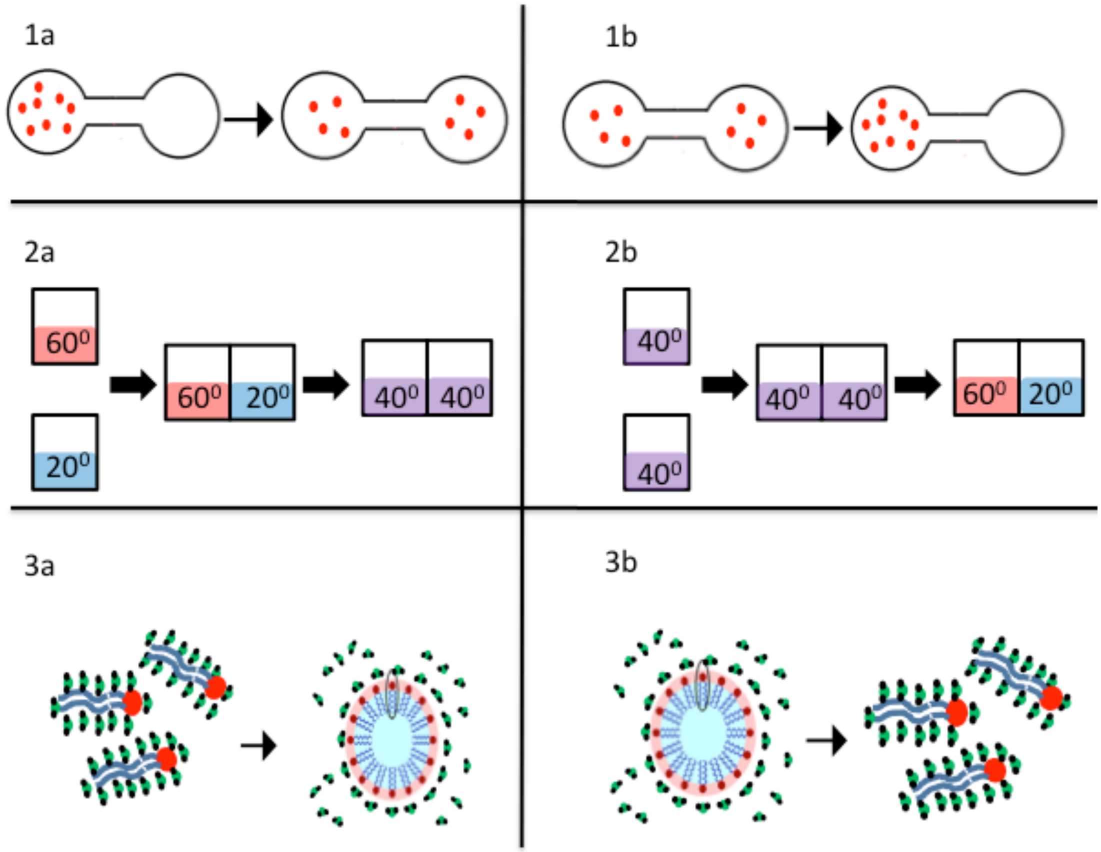


Figure 4.2. Images of slides shown to students during interviews prior to the entropy unit in NEXUS/Physics. Box 1a shows particles filling the available volume during

the free expansion of a thermally isolated ideal gas. Box 2a shows two objects initially at different temperatures (60^0C and 20^0C) brought into contact, and ultimately equilibrating to a common temperature (40^0C). Box 3a shows phospholipid molecules, initially each surrounded by water molecules, self-assembling into an organized micelle. Boxes 1b, 2b, and 3b show the same three processes happening in reverse.

We showed the students three processes – the free expansion of an ideal gas, the equilibration of two objects at different temperatures, and the formation of micelles out of phospholipids in water – and asked the students to describe what they observed happening in each slide. We also showed the students the same three processes in reverse, hoping to prompt discussion about why the forward direction was spontaneous but the reverse was not.

In the case of micelle formation, the water molecules' hydrogen bonding structure is configurationally *restricted* by the presence of phospholipids in solution (the water forms a so-called "hydrogen-bonded cage" structure around the phospholipids), such that the configurational entropy of the water molecules is reduced. Since the phospholipid-water interface area is minimized when the phospholipids self-assemble into organized structures, the entropy associated with the water molecules increases upon micelle formation. To determine the sign of the *overall* entropic change in the system upon micelle formation, one must also take into account any entropic change associated with the *phospholipids* as they go from being dispersed to organized. This change depends on the type and concentration of the phospholipid one is considering (we will return to this issue toward the end of this chapter), but there is a range of conditions under which the overall sign of the system entropic change (considering both water and phospholipid contributions) is positive upon micelle formation. Because there is also a range of temperatures for which the net *energetic* change associated with bond breaking and reforming events in micelle formation is small compared to the entropic effects, the spontaneous formation of micelles is an entropically driven process under a range of biologically relevant conditions (Chandler, 2005).

To help in coordinating student ideas with canonical textbook presentations, we examined the treatment of entropy in the introductory biology, chemistry, and physics textbooks used by life science students at the University of Maryland, College Park (UMCP) (Campbell, et al., 2008; Tro, 2011; Knight, Jones, & Field, 2007). Such disciplinary textbooks differ in both the language they use to describe entropy, and in the examples used to illustrate why entropy is important. Our analysis is in no way meant to be an exhaustive account of the sorts of treatments of entropy and the second law that one might find in various disciplines' textbooks, but rather serves to present typical examples of each discipline's treatment in the hopes of providing context for making sense of our students' ideas.

4.3 Tensions in students' reasoning about entropy and spontaneity

In analyzing student interviews, our focus was on understanding the ideas and resources our students had for thinking about entropy and for using the second law to describe phenomena in the natural world. Prior work has described a number of patterns in undergraduate students' thinking about both entropy (Sozbilir, 2003; Christensen, Meltzer, & Ogilvie, 2009; Bucy, Thompson, & Mountcastle, 2006) and spontaneity (Ribeiro, Costa Pereira, & Maskill, 1990; Sozbilir, 2004), but few attempts have been made to understand student thinking about the second law in biological contexts (Dreyfus B. , Geller, Meltzer, & Sawtelle, 2014). We uncovered tensions between what Tammy, Otto, Elena, and Gavin understood to be true about entropy and what they knew to be true about the spontaneous formation of biological structures. At times students recognized these tensions in their own understanding, and at other times we identified tensions that students did not fully articulate themselves.

4.3.1 Students experience tension between disorder and biological structure

Prior to beginning any discussion of entropy in our NEXUS/Physics course, we asked our case-study students to tell us how they had seen the concept described in their previous biology and chemistry coursework. Their initial responses were fairly uniform, all leveraging ideas about disorder and chaos, and entirely consistent with the descriptions found in standard introductory textbooks.

Gavin said that "entropy is a measure of disorder," and that "generally, the universe is increasing in disorder." Tammy and Otto described entropy as related to "chaos," with Otto referring to an entropy increase as "the increasing chaos or disorganization [in the world]," and Tammy defining entropy as "the amount of chaos that is related to the system." Tammy further specified what she meant by chaos, saying that chaos "can be determined by things like the number of molecules, whether a structure is forming or 'dis-forming'... the type [phase] of matter: solid, liquid, or gas…" Elena was at first uncertain about whether to associate entropy with order or disorder, but was confident that somehow entropy referred to the "order and disorder of a system."

Otto later revised his initial definition of entropy to include what he remembered to be true about the entropy change associated with chemical reactions, saying that, in addition to relating to chaos, entropy is also associated with "breakdown," as when a single mole of some substance breaks into two moles. By way of illustrating his point, Otto wrote down a chemical reaction – the decomposition of carbonic acid – and noted that "there is more entropy [on the right side of the reaction] because you go from one mole of a compound to two moles... it is broken down... so that increases the entropy [just because you have more moles]." Otto even found ways of blending these "chaos" and "breakdown" metaphors for entropy, describing both the chaos of diffusion and the breakdown of chemical compounds as characteristic of processes in which one "loses containment" of the system.

These initial responses were not surprising. All of the case-study students recalled having encountered entropy in a manner consistent with introductory textbook treatments of the topic. In the introductory biology textbook used by our students, for example, entropy is defined simply as "a measure of disorder," with no more precise description or quantitative representation provided (Campbell, et al., 2008). The book notes only that "the more randomly arranged a collection of matter is, the greater its entropy," and that "there is an unstoppable trend toward randomization of the universe as a whole." The introductory chemistry textbook assigned to our students in their general chemistry course introduces entropy in a similar way as the biology textbook, again defining entropy as a measure of disorder in a substance or system (Tro, 2011). One notable way in which the chemistry text differs from the biology text is in its inclusion of a table of absolute molar entropies for various substances, a table whose values are consistent with Otto's understanding that entropy increased upon the breakdown of carbonic acid. When entropy is described qualitatively in the introductory physics text used by students at UMCP who are not enrolled in NEXUS/Physics, it also does so with the familiar refrain that "entropy measures the amount of disorder in a system" (Knight, Jones, & Field, 2007).

For some students, this idea of entropy as disorder is in tension with their knowledge that organized biological structures spontaneously form. Consider, for example, how Gavin talks about his understanding of micelle formation, the process by which phospholipid molecules self-assemble into an organized spherical structure in which the polar heads of the molecules interact with water and the non-polar tails are buried inside (see Boxes 3a and 3b in Figure 4.2):

> *We say that it is thermodynamically favorable for entropy to increase… then why is it that you have situations where cells are going to congregate? [Where] you are going to make organisms? [Where] you are going to make people?... What I know about entropy is what I have been taught… I do not have all the information yet. I have been taught that [micelle formation] happens, I just don't know how it happens.... I know the fundamental properties of these molecules and how they interact with each other but… if you are going to want everything to spread out, then you are going to assume that everything will spread out... but you know the complete opposite happens where it becomes more organized... I feel it disagrees. I feel like it is a lack of complete information. [I have] enough to answer a question on the MCAT but not enough information to have a symposium about how micelles form.*

Accounting for such organized biological structures against the backdrop of the ubiquitous "entropy as disorder" metaphor requires that we think carefully about how to connect ideas about entropy to ideas about spontaneity. Before we turn to this issue and how we might address it, however, it is worth emphasizing that *any* such treatment should take seriously this tension that Gavin articulates. It is natural that IPLS students would feel tension between the second law of thermodynamics and what they know to be true about spontaneous cellular structure formation. While it may be technically sufficient to address the tension by asking students to think about the entropy of the system plus surroundings, rather than just the entropy of the system, it is an empirical question as to whether such an approach in and of itself best leverages student resources for thinking about spontaneity. It is also doubtful that one could reliably determine the sign of the entropy change for *either* the system or surroundings using *only* qualitative ideas about disorder. As we will see, coordinating an approach that addresses the entropy of both system and surroundings with one that addresses the relationship between system free energy and spontaneity may in fact make use of student resources in a promising way.

4.3.2 Tensions exist between colloquial and technical meanings of disorder

There is a second tension that we must consider alongside the tension between disorder and organized biological structure, one that is embedded within the disorder metaphor itself. While the terms "disorder" and "chaos" may well have a very technical meaning to scientists teaching the second law of thermodynamics, people generally mean a wide variety of less precise things when using those words (Styer, 2000; Lambert, 1999; Jeppsson, 2011; Amin, Jeppsson, Haglund, & Stromdahl, 2012; Jeppsson, Haglund, Amin, & Stromdahl, 2013). In this chapter we view the terms "disorder" and "chaos" as virtually interchangeable, since that is what we observe the students doing in our interviews. We recognize, of course, that physicists sometimes use "chaos" to mean something much more specific, as when describing dynamical systems that are highly sensitive to initial conditions. We use "chaos" and "disorder" in the qualitative sense in which the terms are used by students and instructors in the context of entropy.

To see how the technical meaning of "disorder" in the context of the second law of thermodynamics need not align with other plausible meanings of the word, consider how Elena described the PowerPoint slide showing a gas freely expanding to fill a volume (Box 1a in Figure 4.2). She considered the final state to be more "ordered" because she associated order with "the natural state of things." She identified the freely expanded gas as "a more ordered system because [the expansion] would happen naturally... it does not go against nature." While Elena's definition of "order" may contradict the technical sense in which the word is sometimes intended, there is actually nothing linguistically implausible about associating "order" with the natural state of things. Indeed, Elena's mechanistic reasoning about the free expansion is sound: "All the molecules are not going to want to stay in one space, because they are going to be interacting with each other and bumping into each other. [Individually] they will be moving to the right and to the left... and eventually they are going to equilibrate and that [spread out state] is just more ordered."
Elena's description of the free expansion of an ideal gas reveals one pitfall of using a term that has numerous colloquial meanings. Given the imprecise definition of "disorder" and the variety of meanings students may associate with the word, there is no obvious reason to expect students to associate "disorder" with one particular meaning and not others.

Tammy's interview further illustrates this point in her description of the freely expanding gas. Consistent with her definition of chaos as involving more violent and numerous collisions, Tammy said that the gas "has more entropy [before it expands] because... you have more molecules in a smaller volume… and therefore more collisions… If you think about 8 molecules colliding in a tiny container versus 8 molecules colliding in a giant container, the giant container is not going to have as much going on because the molecules are so far [apart], whereas in the smaller container it's much more chaotic... much more going on." In short, Tammy says that the gas freely expands because “it is moving from a more chaotic to less chaotic system, which is more favorable… more balanced.”

Tammy’s reasonable sense of what it means for a system to exhibit chaos (indeed it is a meaning that instructors would likely promote in other scientific contexts), does not match the narrow sense in which instructors mean “chaos” when describing entropy. As a result, Tammy sees the freely expanding gas as becoming less chaotic and must conclude that the entropy decreases in such a process.

One way to resolve the tension between technical and colloquial uses of “disorder” and “chaos” would be to stop using those metaphors entirely when discussing the second law of thermodynamics. This approach, however, not only disregards the entrenchment of those terms in everyday understanding of entropy, but it ignores the highly productive ways in which students can leverage the terms. Approaches that suggest abandoning the use of metaphors like “disorder” entirely when talking about entropy do not consider the second law in an interdisciplinary context (Christensen, Meltzer, & Ogilvie, 2009). Life science students encounter the idea of disorder in their biology and chemistry courses, and sometimes use the idea productively.

In the next sections we highlight some of these productive uses of disorder, and suggest that refining the metaphor and coordinating it with other formulations of entropy may be more effective than trying to eliminate it from our vernacular entirely. A theoretical commitment to leveraging student ideas means treating the disorder metaphor as a resource to incorporate, even if it is, in many cases, insufficient.

4.4 Students have productive resources for making sense of entropy and spontaneity

Our commitment is to leverage the resources that life science students bring to IPLS courses from their experiences in biology and chemistry courses. In this section we describe some of the resources that our students have for making sense of entropically driven processes, and for thinking about the relationship between entropy and spontaneity. We find that the *free energy* of a system – and in particular the way in which energetic and entropic effects determine the change in free energy of a system – plays a central role in our students’ understanding of thermodynamics.

4.4.1 Using disorder to explain diffusion and osmosis

In describing what he meant by chaos, Otto appealed to the process of osmosis. He noted that, as solvent water molecules spread toward regions of high solute concentration, the "water is no longer contained... it is distributed... it is all over the place... you can think of it as a mess." Later he described the water in such a process as going from “a place of order to a place of disorder.” For Gavin, the idea of disorder is central to his understanding of diffusion: “[If you] put a bunch of particles together in a certain area, the particles want to diffuse from one another; they want to spread out; they do not want to be so ordered; they want to increase [their] disorder."

To Gavin and Otto, processes like diffusion and osmosis make good sense in the context of metaphors like “disorder” or “chaos.” The metaphors are well-aligned with their descriptions of these particular entropic phenomena. This would suggest that for Tammy and Elena, whose plausible ideas about “disorder” did not align with the technical meaning of the word in the context of the second law, the challenge is not to replace the word but to refine its definition so as to disambiguate colloquial from technical meanings, and to help them understand the conditions under which certain colloquial meanings are appropriate. A nuanced and technically sound understanding of disorder (perhaps one that is well coordinated with canonical ideas about microstates, for example) would still, however, fail to address the tension between disorder and the spontaneous appearance of order in the biological world. To address that tension, student ideas about the interplay of energy and entropy are particularly relevant.

4.4.2 Spontaneity depends on both energy and entropy

In one way or another, all of the students we interviewed related their understanding of entropy to their understanding of energetic interactions between molecules and, in turn, to Gibbs free energy. When Gavin was confronted with the apparent conflict between his idea of entropy as disorder and his knowledge that micelles form spontaneously in water, Gavin's first looked for an energetic argument that might help with the reconciliation. "If you threw 100 polar molecules in the ocean," Gavin said, "then over time they would spread out as far as they can possibly get until they aren't considered interacting with each other any more." He attributed the observation that such separation does not occur for non-polar lipid molecules to the fact that "entropy [must be considered] relative to interactions... it is dependent on how much force [the molecules] can influence on each other." He then spontaneously brought up the equation relating entropy to Gibbs free energy, $\Delta G = \Delta H - T\Delta S$, and noted that "the higher the entropy, the more negative the free energy, depending on enthalpy in the system… the more spontaneous something is, the higher the entropy in the system." Gavin looked to an interplay between entropic and energetic effects to help him reconcile micelle formation with what he would expect from entropy considerations alone.

Likewise, Otto makes sense of the apparent contradiction between "entropy as chaos" and the spontaneous formation of a micelle in water by noting that, "naturally things just want to go into chaos... but [in micelle formation] that is not really the case because of the polarity that is involved. It is the polarity that is causing it to come together compared to just having things naturally interact with each other." Otto has not carefully thought through the energetic factors involved in the interactions between lipids and water molecules, but his intuition, like Gavin's, is that one must consider those energetic factors alongside the entropic effects in determining whether a structure will spontaneously form.

4.4.3 Using ΔG and spontaneity as a check on ideas about disorder

Tammy, who had a common sense definition of "disorder" that gave entropy the wrong sign, also quickly (and spontaneously) turns to the $\Delta G = \Delta H - T\Delta S$ relation, using it as a check on her previous conclusion that the entropy change would be negative upon free expansion of an ideal gas. Although Tammy fails to recognize that the free expansion is *not* a constant pressure process for which the Gibbs free energy would be applicable (the Helmholtz free energy should be used instead), she does leverage general ideas about free energy productively. She recognizes that a negative ΔS corresponds to a positive ΔG in situations where the enthalpy change is zero, but she knows that the free expansion requires a negative ΔG. “It bothers me,” Tammy says, “because [free expansion] is a spontaneous process and [a positive ΔG] means it is not spontaneous... it is saying that it requires energy… something is overlooked... whether that means there's actually an enthalpy change I am not sure. I am really sure that the ΔG should be negative... because, you know, it is a spontaneous process." Later in the interview, Tammy’s confidence in her reasoning about free energy forces her to conclude that she must have been reasoning incorrectly about the sign of the entropy change.

For Tammy and all the other students we interviewed, the idea that spontaneity requires a negative change in the Gibbs free energy of the system served as a powerful resource for framing a discussion about what entropy can contribute to their understanding of biological phenomena. In fact, across all of our interviews with the case-study students, the notion that spontaneity requires a negative change in the Gibbs free energy of a system was one of the most consistently leveraged ideas, and was well coordinated with other elements of our students’ thermodynamic knowledge.

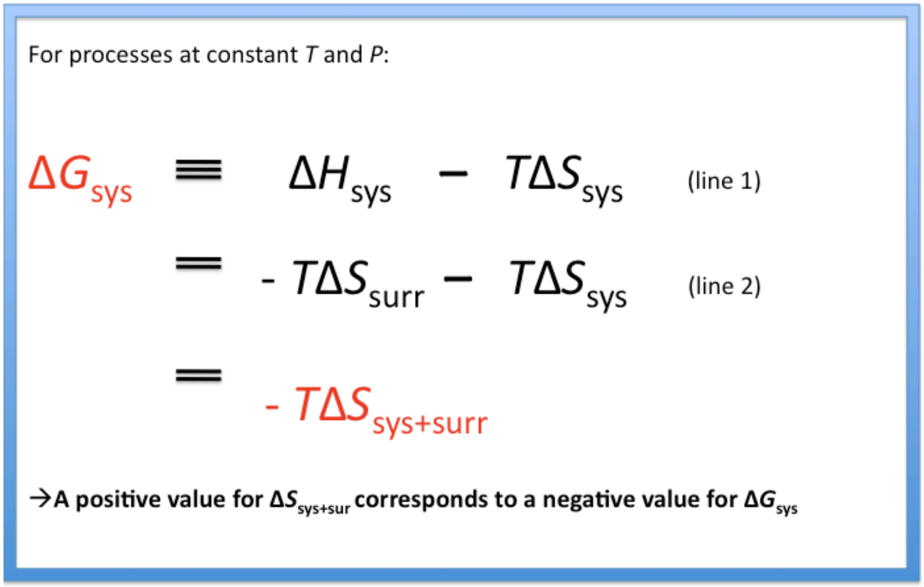
4.5 Pathways toward bridging entropy and spontaneity

The life science students we interviewed had powerful resources for reasoning about spontaneity. The goal in this section is to describe how these ideas can be positioned relative to canonical statements of the second law, and to point toward ways in which one might leverage these ideas in scaffolding tasks that support developing students’ understanding. Our goal is *not* to offer a one-size-fits-all approach to addressing the tensions described earlier in this chapter. Rather, we discuss how our students’ familiarity with free energy suggests one promising route toward bridging ideas about entropy and spontaneity, one that foregrounds a statement of the second law in terms of energetic and entropic changes in the *system*.

4.5.1 Two ways of thinking about the second law of thermodynamics

The second law says that a physical process is spontaneous if it is associated with positive change in the overall entropy of the *system and its surroundings*. Use of this formulation of the second law to predict spontaneity is limited, however, by one’s ability to account for all the entropy changes during a given process. Fortunately, under certain conditions one can re-write the second law such that spontaneity is determined by a property of the *system considered*, and not by a property of the system *plus* surroundings.

At constant temperature (T) and pressure (P), conditions common for biochemical processes, the system property that determines spontaneity is the Gibbs free energy. The Gibbs free energy differs from the Helmholtz free energy in that the former is a measure of the amount of chemical work that one can obtain from a thermodynamic system at constant T and P, whereas the latter measures the obtainable work when only T and V are constant (Schroeder, 2000). At fixed T and P, the Gibbs free energy can only change when the number of molecules of some species changes during some process. For this reason, the Gibbs free energy is of particular importance to chemists concerned with chemical reactions in which the number of molecules of one or more species changes. Figure 4.3 demonstrates the relationship between the entropy of the system plus surroundings and the Gibbs free energy of a system.



For processes at constant T and P:

$$\Delta G_{sys} \equiv \Delta H_{sys} - T\Delta S_{sys} \quad \text{(line 1)}$$

$$= -T\Delta S_{surr} - T\Delta S_{sys} \quad \text{(line 2)}$$

$$= -T\Delta S_{sys+surr}$$

→**A positive value for $\Delta S_{sys+sur}$ corresponds to a negative value for ΔG_{sys}**

Figure 4.3. For any process that occurs at constant temperature (T) and pressure (P), the Gibbs free energy of a system changes in a way that mirrors the entropy change of the system plus surroundings. As such, the sign of the system's Gibbs free energy change during a process determines whether the process is spontaneous. Line 2 is equivalent to line 1 because the enthalpy change for a system at constant T and P, ΔH_{sys}, is equivalent to the heat transferred with the surroundings, $-T\Delta S_{surr}$. Schroeder (2000) provides more detailed relations between enthalpy, heat transfer, and $T\Delta S$.

When the entropy of the system plus surroundings increases during a process, the Gibbs free energy of the system decreases, and the process is spontaneous. When the entropy of the system plus surroundings decreases during a process, the Gibbs free energy of the system increases, and the process does not spontaneously proceed.

The relationship between the system's Gibbs free energy change and the entropy change of the system plus surroundings suggests two possible ways of connecting ideas about disorder with the spontaneous formation of organized structure. On the one hand, biological structure formation can be reconciled with the second law of thermodynamics by considering not just the entropy of the system, but also the entropy of the surroundings (line 2 in Figure 4.3). This approach requires that one have some way of measuring entropic changes not just in the local system one is investigating, but *everywhere*. In predicting the spontaneity of micelle formation, for instance, one would not only need to measure the entropic changes for the phosopholipid and water molecules in the system, but also for everything else in the surroundings that was changed due to the process being considered. This is an approach to conceptual reconciliation that has been previously discussed in the literature (Toussaint & Schneider, 1998), and one that many physicists are familiar with employing when confronted with the question of how organized structures form.

A second approach to reconciling biological structure formation with the second law of thermodynamics is to consider the interplay of energetic and entropic effects on the *system itself* (line 1 in Figure 4.3). Our case-study interviews with students prior to the entropy unit in our course suggest that this approach may draw on students' experiences in biology and chemistry in particularly effective ways. Indeed, the introductory biology and chemistry textbooks that our students use *introduce* entropy by way of its contribution to the Gibbs free energy (Campbell, et al., 2008; Tro, 2011). The very first time that the symbol S appears in their biology text is in the equation $\Delta G = \Delta H - T\Delta S$, wherein an increase in entropy is one way to achieve a decrease in Gibbs free energy G (Campbell, et al., 2008). The introductory chemistry textbook introduces entropy in a very similar way, positioning entropy as one of the factors that one must consider in determining the sign of ΔG (Tro, 2011).

By way of contrast, the introductory physics textbook used by life science students at UMCP *not* enrolled in NEXUS/Physics never mentions the role that entropy plays in determining the change in free energy during a physical process. In fact, despite its central role in the biological and chemical sciences, free energy is not considered anywhere in the entire introductory physics textbook. (The NEXUS/Physics course does not use a textbook, but assigns numerous online readings, as described in Redish et al. (2014)). By describing the second law not just in terms of the entropy of the system plus surroundings, but also in terms of the Gibbs free energy in a system, IPLS courses can play a critical role in bridging the divide between canonical treatments of entropy in different disciplines.

4.5.2 Leveraging students' ideas: A sample activity

The student data in our IPLS course suggest that meeting our students where they are means leveraging their familiarity with Gibbs free energy in making sense of the second law of thermodynamics. Fortunately, a treatment of spontaneity that emphasizes the interplay between energy and entropy is one for which an introductory physics course is naturally well-suited. Unpacking the mechanistic underpinnings of entropy and enthalpy, the combination of which determines spontaneity in biological processes, is not always feasible in introductory biology and chemistry courses.

IPLS courses can play an important role in encouraging students not just to *associate* spontaneity with a negative change in Gibbs free energy, but to understand *how* and *why* that negative sign emerges from energetic and entropic contributions. This is not to suggest that one should ignore other approaches to the second law, ones that consider the entropy of the surroundings along with that of the system. Indeed, the two approaches are of course complementary and, when employed thoughtfully, should only serve to reinforce each other. Our claim is only that we do our life science students a disservice when we do not provide them with opportunities to explicitly connect their understanding of Gibbs free energy with a formulation of the second law.

To begin to provide such opportunities in our NEXUS/Physics course, we designed two small group problem-solving tasks to be completed in two 50-minute class sessions over consecutive weeks. We describe some features of these activities not because we view them as final products to be adopted, but because they illustrate some ways in which task design can attend to the tensions students describe and make productive use of student resources.

The first task asks students to examine in a qualitative way why it is that oil and water spontaneously separate under certain typically-encountered conditions (including conditions of standard temperature and pressure, with oil sizes and concentrations encountered regularly in daily life), *i.e.*, it was designed to begin to unpack the entropic underpinnings of the hydrophobic effect. The task is scaffolded with open-ended questions prompting the students to consider differences in the molecular degrees of freedom between the state in which oil molecules are dispersed homogenously throughout a volume of water and the state in which the oil and water regions are separate. The questions aim to problematize the idea of disorder by pointing out that one cannot uncritically assume that the state in which oil and water are homogeneously mixed (the superficially "disordered" state) is the higher entropy state.[13]

The second task builds on the first to explore the formation of lipid bilayer cell membranes. In this task, students weigh the competing effects of enthalpy and entropy in a qualitative way, accounting for the many factors that go into determining spontaneity for a complex, authentic biological process. They determine which bond-breaking and bond-forming events one would have to take into account in determining the sign of the enthalpy change during bilayer formation. In considering these enthalpic effects, students call upon their ideas about electrostatics in the context of a thermodynamics task, thereby linking two realms that could all too easily remain disconnected in introductory physics courses. This activity helped make explicit the tension between disorder and the formation of organized structures like the lipid bilayer cell membrane, and asked students to make use of their resources for thinking about Gibbs free energy in order to resolve the tension. At room temperature, it turns out that the net *enthalpic* change ΔH associated with bond breaking and reforming events in bilayer formation is small compared to the entropic term $T\Delta S$. As a result, at room temperature the entropic effect drives the spontaneous bilayer formation process.[14]

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[13] As noted earlier in the chapter, it is a complicated business to determine the conditions under which oil and water spontaneously separate. Factors like the concentration and size of the oil molecules play a role in determining whether the oil will clump, as does the temperature at which the substances interact. Because the objective in our introductory physics course for life science students is not to explore in detail all the conditions under which oil and water *might* mix, but rather only to consider in a *qualitative* way the factors that contribute to the separation of oil and water under biologically relevant conditions when the separation *is* in fact spontaneous, we choose not to explore the dependence on oil concentration and size in any detail. Those dependences are discussed elsewhere (such as in Chandler (2005)).

[14] This is not to say that there are not temperatures for which the enthalpic term might dominate, but again our aim in these tasks was not to consider *all possible* conditions under which one might attempt to mix phospholipids with water. Rather, we were interested in developing a qualitative sense for the factors that one must consider when determining why it is that lipid bilayers form spontaneously in the cell. For that purpose, it is sufficient to note that, under many biologically relevant conditions, the energetic term is small compared to the entropic term.

The intention of these tasks is not to arrive at a quantitative result, but rather to address tensions surrounding entropy and spontaneity, and to help students better understand the relative roles of entropy and energy in driving the separation of oil and water. Designing open-ended, discussion-provoking tasks of this nature is challenging (Gouvea, Sawtelle, Geller, & Turpen, 2013). It is inevitably a highly iterative process in which student feedback plays an essential role in task design, and in which one must be willing to be led in unexpected directions by insightful student ideas.

We have implemented the two-week task twice, in slightly different forms, and the third version will incorporate even more changes inspired by our discussions with students and by what we have learned during our two years designing an IPLS environment. We have preliminary evidence from thermodynamic surveys, in-class discussions, and case-study interviews that students find these tasks to be valuable in helping them build connections even in these early stages of design. In interview settings and more informal discussions outside of class, students have described the oil and water tasks as helpful in refining their intuitions about entropy. We therefore do not suggest that one must wait until the tasks do exactly what one intends them to do before using them productively. Rather, we provide this example as a way of encouraging IPLS instructors to consider and see as feasible the design of tasks that generate thoughtful discussions about the second law and Gibbs free energy. Leveraging student resources from biology and chemistry in task design can help students build conceptual bridges across their biology, chemistry, and physics courses.

4.6 Conclusion: Toward great coherence between disciplinary treatments of entropy and spontaneity

We argue that a coherent treatment of the second law of thermodynamics in IPLS courses is important both in terms of the phenomena it allows students to understand and in terms of the tensions it allows students to resolve. These tensions are visible in students' nascent understandings of the second law, as they seek to make sense of (1) how technical and colloquial meanings of disorder are related, and (2) the apparent contradiction between the spontaneous formation of highly organized biological structures and a rule that says that disorder is always increasing in spontaneous processes. We have also articulated a number of productive resources that student bring into our course context, and we should build from these resources in pursuing resolutions to these tensions.

The student reasoning presented in this chapter call for a treatment of entropy in IPLS courses that emphasizes its role in determining the spontaneity of processes, including biological ones. Students develop intuitions for such spontaneity in their introductory biology and chemistry courses, and for the relation of spontaneity to the sign of the change in Gibbs free energy. In particular, students display an intuition that spontaneity depends on both energetic interactions and entropy, and an instinct to use sign of ΔG as a check on their analyses of entropy changes. The resources theoretical framework suggests that we would be well served to leverage and refine these intuitions when introducing the second law of thermodynamics.

Unpacking the complex interplay between energy and entropy in determining the sign of the free energy change requires that we develop a set of illustrative and discussion-generating problems that help students understand these sometimes competing effects. We have described concrete example tasks which serve to illustrate the path forward that we propose, though much curriculum development is left to do. The burden for developing such curricula lies on the shoulders of *both* IPLS instructors and those teaching introductory biology and chemistry courses. The benefit of doing so is that our students will have opportunities to explore the thermodynamic world in a more coherent way.

Chapter 5: Bridging the gaps: Classifying forms of disciplinary boundary crossing in NEXUS/Physics[15]

5.1 Introduction: Identifying and bridging disciplinary silos

Few opportunities exist for life science students to see different disciplinary explanations as meaningfully related, let alone as part of a coherent whole (Donovan, et al., 2013; Hartley, Momsen, Maskiewicz, & D'Avanzo, 2012; Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014; Dreyfus, Gouvea, Geller, Sawtelle, Turpen, & Redish, 2014; Redish, et al., 2014). Life science students encounter disciplinary "silos"[16] 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. The fragmentation is not limited to the experience of undergraduates, and in fact may exist for much younger school children as well (Stevens, Wineburg, Herrenkohl, & Bell, 2005).

One of the primary goals of NEXUS/Physics, a novel introductory physics course for life science students, is to provide students with an opportunity to bridge these disciplinary divides. By leveraging students' understanding of biology and chemistry in the context of a physics course, our aim is to foster more coordinated understanding of authentic biological phenomena. The goal of this chapter is to identify three *classes* of interdisciplinary connections that students have made in NEXUS/Physics. The three classes of connections we identify are not the only possible connections that students might make in an IPLS course, but they "span the space" of interdisciplinary connections that we have observed over three years of implementing our course. Each of these classes coordinates students' conceptual and epistemological resources from physics, chemistry, and biology in distinct but complementary ways. As we will see, they are accompanied by markers of affect, often indicating a sense of resolution or satisfaction expressed by the students in having bridged a disciplinary divide.

5.1.1 Different disciplines answer different questions

Part of the challenge in fostering interdisciplinary boundary crossing is that different disciplines ask different questions. Even when a life science student is fortunate enough to encounter the same biological *phenomenon* in different courses, the *questions* asked about that phenomenon in physics class may be so different in nature from those asked in biology class that the student may not see the two discussions as meaningfully related.

Consider, for example, the lipid bilayer structure of cell membranes in biology. Biological cell membranes are composed of phospholipid molecules arranged in a particular orientation so as to minimize the interaction of the non-polar

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[15] This chapter is being prepared for submission to *Phys. Rev. ST-Phys. Educ. Res.*

[16] "Silos" are used in agriculture and farming, primarily for separating the bulk storage of various grains. The term has been adopted in interdisciplinary education literature to refer to the fragmented nature of students' disciplinary experiences.

hydrocarbon lipid tails with the polar (aqueous) environment of the cell. Where a biology course might be interested in probing the evolutionary advantage or cellular-level functioning of a lipid bilayer cell membrane ("why did the membrane evolve?"), an interdisciplinary physics course might examine in detail the energetic and entropic contributions to the stability of that membrane ("what is the mechanism by which the membrane forms?"). In this example, the common biological *phenomenon* – the piece of the biological world that we are trying to explain – is the stability of the bilayer cell membrane. Because the questions that one asks about this common phenomenon are so different across the disciplines, however, students may not appreciate the potential for coordination between their courses in the way that we would hope. Being explicit about these differences in the questions themselves can be an important first step toward supporting a more coherent experience.

Because the questions that different disciplines ask about biological phenomena are different, it is not surprising that the explanatory pathways – the chains of claims and warrants that are employed to answer the questions – are different as well. An important feature of many of the tasks in NEXUS/Physics is an exploration of *multiple* explanatory pathways related to a biological phenomenon.

To make this concrete, consider again the lipid bilayer structure of cell membranes. The spontaneous formation of cell membranes is sometimes described in introductory biology and chemistry courses via the heuristic "like dissolves like," a rule of thumb referring to the idea that solutes will dissolve in solvents only when both solute and solvent molecules exhibit similar chemical polarities (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014). The "like dissolves like" heuristic is used to account for the separation of oil and water and, in the biological realm, to account for the formation of lipid bilayers.

The warrant "like dissolves like" is itself a claim in need of justification. The nature of that justification depends on the question that one is trying to answer, and therefore varies across disciplinary boundaries. Biology courses that explore the evolutionary advantage of biological structures may ultimately answer the question of why stable bilayer structures exist in terms of the evolutionary advantage of cell compartmentalization and the ability to separate intra- and extra-cellular environments (right third of Figure 5.1). Chemistry courses may not discuss evolution at all, but may instead describe bilayer formation and the "like dissolves like" heuristic in terms of Gibbs free energy. That is, chemistry courses might stress that the spontaneity of lipid bilayer formation, like the spontaneity of any biochemical processes occurring at constant temperature and pressure, is associated with a negative change in the free energy of the system (Levine, 1978). In turn, this negative change in free energy can be understood as resulting from the interplay of the energetic and entropic terms in the free energy expression $G = H - TS$ (middle third of Figure 5.1).[17]

Because a physics class might focus on the mechanism by which lipid bilayers come to exist in aqueous environments, rather than on the evolutionary advantage of such structures, detailed analysis of the electrostatic interactions between individual

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[17] Gibbs free energy is particularly useful in biology and chemistry because the temperature and pressure are often considered constant during biological processes and chemical reactions.

lipid and water molecules, and of the degrees of freedom available to those molecules, would be located within a physics explanatory pathway (left third of Figure 5.1).[18]

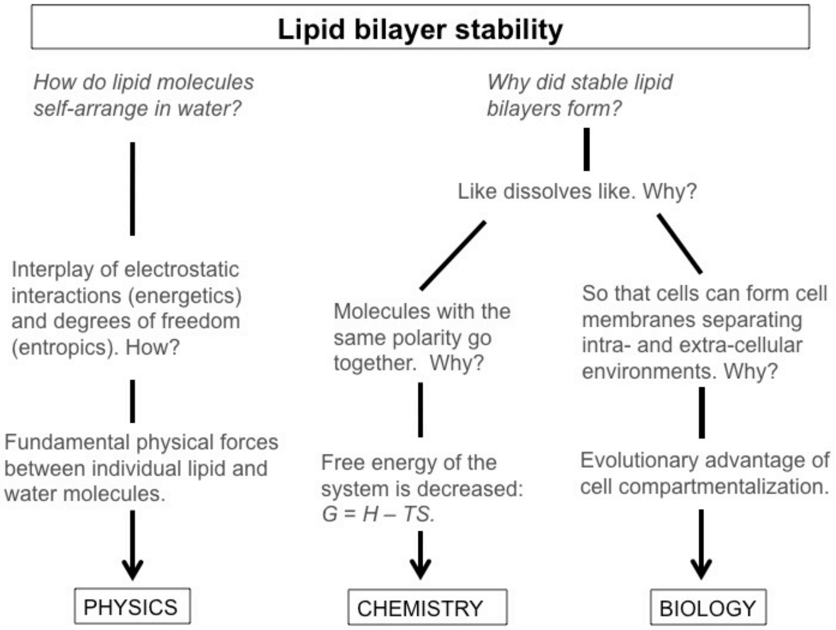

Figure 5.1. An explanatory framework depicting disciplinary ideas associated with lipid bilayer stability.

The explanatory framework depicted in Figure 5.1 is meant to be simplistic. In practice, explanatory pathways that answer particular questions might involve substantially more branching and fuzzier disciplinary boundaries. Biology courses do not only ask structure-function questions about evolution, chemistry courses do not only describe the spontaneity of processes in terms of Gibbs free energy, and physics courses do not always go into mechanistic detail. Our goal in providing explanatory frameworks like that in Figure 5.1 is not to comprehensively represent the complex interdisciplinary network of ideas related to a biological phenomenon, but rather to identify a set of prominent guideposts defining the disciplinary silos that our students encounter in their introductory science coursework. These guideposts help us to identify classes of interdisciplinary connections made by students in our IPLS course, and to identify boundaries that students find particularly satisfying to cross.

As we will see, the locations of particular claims and warrants within particular disciplinary silos are motivated primarily (but not exclusively) by our IPLS students' own words. Our students see certain ideas as coming from biology class, and others as coming from physics class. Often these assignments are closely tied up with a student's disciplinary epistemology, his or her sense of what it means to do

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[18] Chemistry courses might also describe the spontaneous formation of lipid bilayers in terms of a balance between enthalpy and entropy, but rarely would such courses delve into the fundamental forces responsible for the values of these terms.

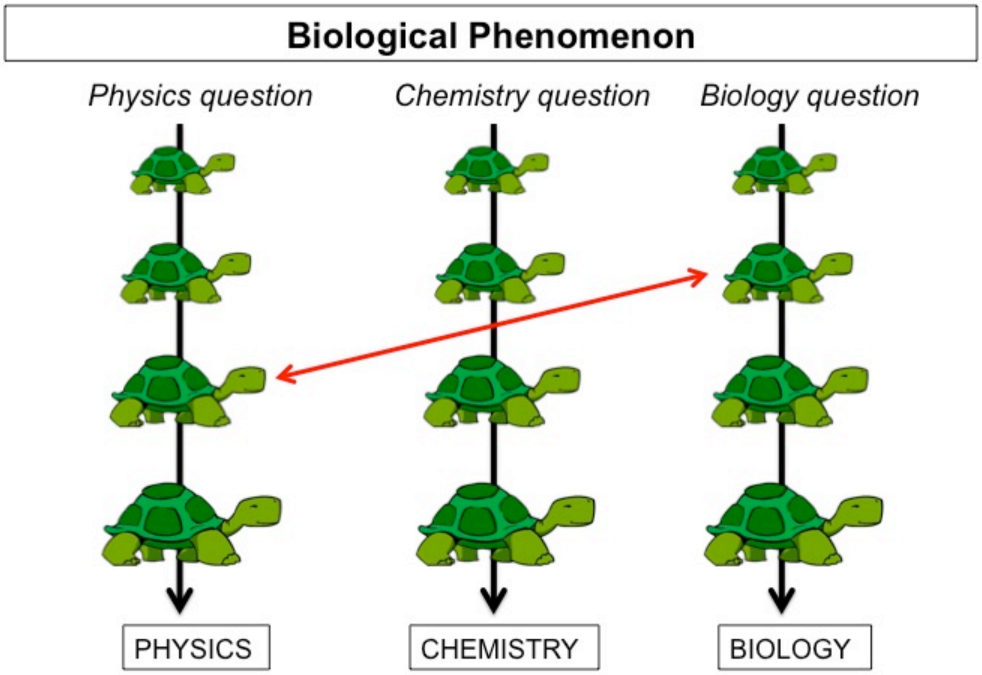
biology or physics. Wherever connections are identified as interdisciplinary in the analysis that follows, it is because the students themselves have tagged the ideas they are coordinating with distinct disciplinary labels.

5.1.2 Interdisciplinary connections bridge disciplinary silos

Throughout this chapter we will encounter explanatory frameworks of a similar form to Figure 5.1. In each case, students see different disciplines as asking different questions about a particular biological phenomenon. As one moves down a given discipline's explanatory silo, answered questions present new questions themselves, such that each step in the explanatory chain is both a warrant (a justification) and a claim in need of further explanation (Bing & Redish, 2009; Bing & Redish, 2009a).

The heuristic "like dissolve like," for example, may be an answer to the question of why stable lipid bilayers form, but it also presents a new question ("why does like dissolve like?") in need of further justification. This chain of questions and answers stemming from a particular disciplinary question form what we are calling the discipline's "explanatory silo." The silos proceed downward in a regress that ends only when one encounters a discipline's fundamental axioms.

Figure 5.2 presents an interdisciplinary explanatory framework in its most general form. Turtles are used to represent steps in the explanatory chain, in reference to the "turtles all the way down" expression of the infinite regress (Hawking, 1988; Sabin, 1905; Barker, 1854).[19]



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[19] The metaphor may stem from an anecdote in which it is argued the Earth is flat, but supported on the back of a turtle which itself is supported up by a chain of larger and larger turtles. Questioning what the final turtle might be standing on, the anecdote concludes with the expression that it is "turtles all the way down". Like the anecdote's stack of turtles, the chain of warrants and claims used to answer questions about biological phenomena proceed downward within any discipline.

Figure 5.2. 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. The red arrows represent interdisciplinary connections made by students.

In the representation shown in Figure 5.2, the arrows representing interdisciplinary connections move horizontally across disciplinary boundaries, linking particular warrants or claims ("turtles") across those disciplines. These interdisciplinary connections, like vines wrapped around parallel pillars, serve to strengthen one's overall understanding of the original 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.

Beginning in Section 5.3, we identify *three classes of interdisciplinary connections*, three broad ways in which students have formed meaningful interdisciplinary links in NEXUS/Physics:

- Connecting biochemical **heuristics** to a physical picture of microscopic interactions
- Connecting physical and biochemical concepts through **mathematical bridging equations**
- Connecting **mechanistic and functional explanations** for biological phenomena

Instances of these interdisciplinary links are represented the red arrows in Figure 5.2. By categorizing these connections, we hope to point out the multiple ways in which productive interdisciplinary sense making happens. These categories represent distinct but complementary ways in which students coordinate disciplinary concepts and epistemologies in NEXUS/Physics. Before fleshing out that discussion, we examine the process by which this categorization was established.

5.2 Methodology

All data in this chapter is drawn from the NEXUS/Physics course at the University of Maryland, College Park (UMCP) (Thompson, Chmielewski, Gaines, Hrycyna, & LaCourse, 2013; Redish, et al., 2014). We draw primarily on two sources of student data: interviews conducted with students over the two-semester course, and video of students working together in small groups on weekly problem-solving tasks. Twenty-two (approximately hour-long) interviews were conducted with 11 students during the first iteration of NEXUS/Physics, a year-long class taken by 31 students during the 2011-2012 academic year. The second iteration of NEXUS/Physics was offered to 31 students during the 2012-2013 academic year, from which a total of 26 (also hour-long) interviews were conducted with 12 students. In all, the 23 students that were interviewed a total of 48 times represent more than 1/3 of the students enrolled in the course over two years. In addition to these interviews, small group problem-solving sessions were filmed on a weekly basis throughout each semester of NEXUS/Physics. Because our course has a year of biology and a semester of chemistry as prerequisites, our assignments and small group problem solving sessions leverage our students' familiarity with the material in those courses by introducing authentic biological problems from the beginning.

Interviews conducted in NEXUS/Physics served multiple purposes. In order to get a sense for how our students had been exposed to concepts like energy and entropy in prior biology and chemistry coursework, we interviewed students early in the course about their previous interactions with topics that would be covered in our course. As the year progressed, interviews provided an opportunity for students to further articulate reasoning that we may have observed in lecture, on exams, or in problem-solving sessions. Students were given also given space in these interviews to describe moments in the course that stood out to them as particularly meaningful.

The weekly problem-solving (recitation) sections provided an opportunity for students to work in groups of four on problems that explored rich biological contexts. Each recitation section was facilitated by one Teaching Assistant (TA) and one or more undergraduate Learning Assistants (Otero, Pollock, & Finkelstein, 2010). These sections were one of the best opportunities in the course for students to explore the relationship between physical models and biological phenomena. Recitation tasks were designed with specific intent to draw on students' ideas from biology and chemistry, often with the goal of reconciling those ideas with newly learned principles of physics.

The case-study interviews and problem-solving sessions produced a wealth of student data. A select number of episodes were chosen for inclusion in this chapter because they represent instances in which students make meaningful progress (or describe having made meaningful progress) in interdisciplinary sense making. This progress was most often accompanied by noticeable *affect*, by a sense of resolution or satisfaction expressed by the students in having bridged a disciplinary divide. As researchers, this affect served as a useful indicator that the episode was worth exploring in detail. Our goal was then to unpack the conceptual and epistemological *sources* of the observed affect, to understand and classify the nature of the interdisciplinary connection that was meaningful to our students. In Section 5.6.2 we describe how the examples that we have selected span the space of interdisciplinary connections that we have observed in NEXUS/Physics, and argue that they are representative of the sorts of connections we see students making in the course more generally.

Episodes in this analysis are labeled as *interdisciplinary* when multiple disciplinary markers are made explicit by our students. When students describe connecting ideas from biology with ideas from physics, for example, that connection is treated in this analysis as an interdisciplinary one, regardless of whether we as researchers might quibble about the disciplinary labels. For the most part, however, there were few inconsistencies between our own views of canonical disciplinary boundaries and those of our students.

We now consider the three classes of interdisciplinary connections that students have made in our course, those listed in bullet points at the end of Section 5.1. We present these types of connections in Sections 5.3, 5.4, and 5.5 by way of examples selected to illustrate their value in concrete contexts. After establishing the nature of these three classes of connections, we will argue in Section 5.6 that they span the landscape of interdisciplinary connections that we have observed in NEXUS/Physics.

5.3. Connecting biochemical heuristics to a physical picture of microscopic interactions

One goal of our IPLS course is to unpack the physical mechanisms underlying biological phenomena that are only described phenomenologically in typical introductory biology and chemistry courses. An example of this is the diffusion of particles or gases along a concentration gradient, a phenomenon with which life science students become familiar but for which they are often not provided a mechanistic explanation in their introductory biology or chemistry courses (Redish & Cooke, 2013; Geller, Gouvea, Sawtelle, & Turpen, 2014).

The discussion of diffusion in NEXUS/Physics emerges from curricular thread focused on the relationship between random and directed motion. In particular, a task on 1D random walks affords students the opportunity to prove that particles tend to spread out to fill the space available to them. The task asks students to make sense of the tendency for particles to go from high to low concentrations in terms of the collisions with nearby particles and a minimal amount of probabilistic reasoning. Students are prompted to extrapolate from the 1D diffusion example in order to prove that macrostates associated with a greater number of microstates are more likely, and to associate entropy with this measure. The spontaneous increase in entropy is seen as arising not just from an abstract “counting” of available states (as is emphasized in a traditional coin-flipping example) but from real microscopic physical interactions.

Diffusive (passive) transport plays an essential role in numerous biological processes (Nilsson G. E., 2010; Evans & Von Caemerer, 2010), but introductory biology and chemistry courses rarely have the time to devote to unpacking the molecular mechanism for such diffusive motion. Gavin, a case study student in NEXUS/Physics, finds the unpacking of diffusion in mechanistic terms to be highly satisfying and references this example in describing the role that NEXUS/Physics plays in his education more generally:

> (1) Gavin: This [NEXUS/Physics] class was very good about telling us about thermodynamics and entropy's role in the universe… 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 *that's* why molecules go from higher concentration to lower concentration...
>
> (2) Interviewer: So you already knew that it happened?
>
> (3) Gavin: I knew that it happened but then I was like how the hell do they know where the lower concentration is?! 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. And that's why I struggle with [organic chemistry] so much, because it's like 'memorize the mechanisms and take the test' (throws up his hands)… well how the hell do I know why the mechanism is happening in the first place?!

(4) Interviewer: How do the molecules know what to do...

(5) Gavin: Exactly. And why do they do this bouncing thing (moves hands back and forth) and it was never explained to me very well, and then when I take this [NEXUS/Physics] class and understand, oh, *this* is why molecules interact the way they do, *this* is why you are going to have this expansion of particles over space.

(6) Interviewer: Yeah.

(7) Gavin: 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 to have the most microstates which is therefore going to have the greatest entropy.

(8) Interviewer: So it connected... you knew that it wanted the greatest entropy, and it connected sort of underneath it what was causing?

(9) Gavin: Right it gave me a foundation...

(10) Interviewer: And that was satisfying to you?

(11) Gavin: 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.

Although Gavin is not entirely "correct" in his description of the physical mechanism underlying diffusion,[20] it is clear that he senses that such a description is possible. This exchange illustrates the nature of the interdisciplinary connection that Gavin has made, as well as his satisfaction in having made it. Figure 5.3 shows the particular ideas that Gavin has coordinated across the explanatory framework for diffusion. Unpacking heuristic statements like "particles know to go from high to low concentration" in terms of the underlying physical interactions between individual particles puts Gavin's overall understanding of diffusion on a more solid (better integrated) foundation.

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[20] Gavin has misidentified the collisions among the molecules of interest rather than the collisions with the surrounding fluid (thermal bath) as responsible for the random walk of the diffusing molecules.

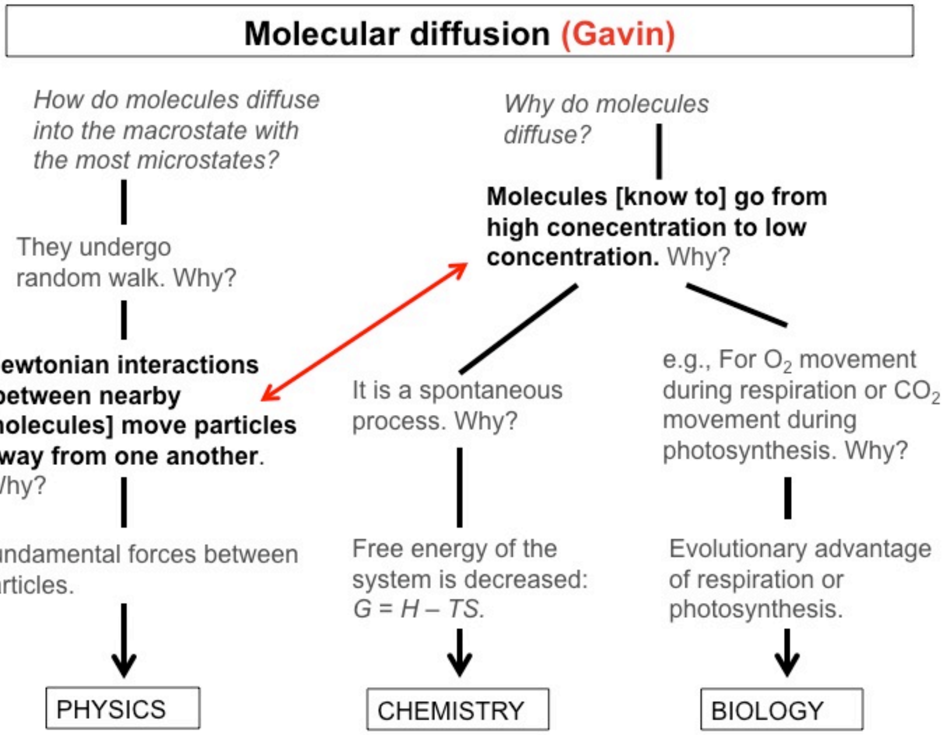

Figure 5.3. Gavin coordinates his resources for thinking about molecular diffusion, unpacking the molecular interactions that cause particles to move from high to low concentration. Words in bold are Gavin's own words. The other (plain text) warrants and claims place his words within the context of possible explanatory silos related to diffusion.

Gavin identifies the heuristic about particles going from high to low concentration as one that comes from his biology and chemistry courses, and identifies the unpacking of diffusion in terms of collisions with nearby molecules as happening in physics class. Gavin himself does not explicitly ask all the questions (nor does he provide all the answers) listed along the explanatory silos in Figure 5.3. Rather, these questions (and their possible answers) are meant to represent the space in which Gavin is reasoning. The questions frame Gavin's explicit connection between a heuristic and fundamental physical interactions (bolded in Figure 5.3) in terms of the disciplinary explanatory silos in which these ideas about diffusion are often encountered. As detailed in Section 5.1, our goal in providing an explanatory framework such as this (and not *just* Gavin's own words) is not to comprehensively represent the complex interdisciplinary network of ideas related to diffusion, but rather to identify a set of prominent guideposts defining the disciplinary silos that our students encounter. Because the NEXUS/Physics course asks questions about the mechanisms underlying diffusion that neither introductory biology and chemistry courses nor traditional introductory physics courses typically ask, the course bridges a gap that might not otherwise have been bridged.

In turn (3) of the interview exchange, Gavin reflects on his experience in biology and (organic) chemistry courses. He diagnoses biology as descriptive and fact-driven ("they have to go over so much stuff"), and as placing too great of an emphasis on memorization of factual information and too little of an emphasis on the explication of "why things happen." In this context, Gavin's "why" questions would perhaps better be interpreted as "how" questions, since it is not clear that an evolutionary answer to "why particles diffuse" would elicit for Gavin the same satisfaction that we see in the above exchange.[21]

The difference between Gavin's epistemological orientations toward biology and physics in this moment is apparent, and is largely responsible for his seeing the mechanistic account of diffusion as being a "physics" account. Gavin's epistemological orientation toward biology in this moment is one in which he sees the discipline as failing to take up mechanistic explanations of the sort that NEXUS/Physics provides for diffusion (or perhaps even failing to ask questions for which a mechanistic answer is appropriate). His arm movements and tone both convey frustration with such a misalignment. On the other hand, where Gavin's epistemological orientation toward biology is in tension with his identification as a "why kind of person," his epistemological view of physics as a place where sense-making happens *aligns* with this identity in such a way that his words suggest an affective response to physics that is notably more positive (Geller, Gouvea, Sawtelle, & Turpen, 2014). He describes being "very satisfied" by the explanation in physics class, and feeling more "confident." We will return to these affective issues in Section 5.6.4.

The diffusion example is not meant to suggest that heuristics are not used in physics, nor that mechanistic explanations do not appear in biology. Rather, we use the Gavin example to illustrate a class of connections of the type illustrated in Figure 5.3, in which students themselves see physics as providing mechanistic "turtles" that support their understanding of biochemical heuristics.

The Gavin episode points to one way in which heuristic biochemical statements about emergent phenomena can be coordinated with fundamental physical principles. Namely, the phenomena described by the heuristic can be seen as directly emerging from a detailed analysis of the interactions of the microscopic particles involved in the process. Gavin develops a physical picture for how individual molecules bump into each other, and how such random collisions between molecules can generate directed bulk motion.

5.4 Connecting physical and biochemical concepts through mathematical bridging equations.

For biological processes in which intermolecular interactions cannot be ignored (which is most of them), detailed mechanistic accounts of the motions of individual particles are impractical. Nevertheless, we observe students making meaningful interdisciplinary connections between biochemical heuristics and fundamental

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[21] Indeed, in an interview conducted with Gavin several months after the conclusion of NEXUS/Physics, Gavin reiterates that being able to run a simulation of the diffusive process in his mind, being able to picture the intermolecular collisions between diffusing particles, is tied up with his sense that he "understands" diffusion.

physics in these cases as well. In these cases when detailed physical accounts are not possible (nor practical), we observe *mathematical relationships* playing a central role in students' sense that their understanding from different disciplines is related and coherent. In particular, in NEXUS/Physics the Gibbs free energy relationship, $G = H - TS$, becomes an essential *bridge* between the spontaneity of biological processes (as indicated by a negative change in the Gibbs free energy G) and the physical factors that determine the enthalpy H and entropy S. The Gibbs free energy relationship is used throughout introductory biology and chemistry courses, but is rarely discussed at all in standard introductory physics courses (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014).

As we will discuss in Section 5.6.1, not all mathematical relationships are created equal in their capacity to bridge physical and biological ideas. The Gibbs free energy relationship is a particularly useful link between fundamental physical and biochemical ideas (in a way that, say, $F = ma$ is typically not). In this section we explore two examples where students make meaningful interdisciplinary connections by examining the Gibbs free energy relationship through the lens of NEXUS/Physics.

5.4.1 Using the Gibbs free energy expression, $G = H - TS$, to unpack the "like dissolves like" heuristic

The observation that oil and water do not mix is identified in many introductory biology and chemistry courses as an example of the widely stated heuristic, "like dissolves like" (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014). This rule of thumb refers to the idea that solutes will dissolve in solvents only when both solute and solvent molecules exhibit similar chemical polarities. 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" is frequently used as a heuristic device to predict that oil and water do not mix. It is also used to describe the formation of lipid bilayer cell membranes, as mentioned earlier in this chapter and depicted in Figure 5.1.

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. Indeed, 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 device.

All else being equal, the electrostatic interaction between a polar molecule like water and a non-polar molecule like oil is stronger than the electrostatic interaction between two oil 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 *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*. When one considers the entropic effects at play in the oil and water example, it becomes clear that the hydrophobic effect is in fact entropically-driven.

“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 (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014), and often not even in the same course (for example, electrostatics is typically a second-semester introductory physics topic, whereas thermodynamics is often covered in the first semester if it is covered at all), the two ideas are not easily reconciled in practice.

Elena, a case study student in NEXUS/Physics, was interviewed about her understanding of the oil and water phenomenon. Recognizing that the electrostatic attraction of a non-polar molecule to a polar molecule was greater than the electrostatic attraction between two non-polar molecules, Elena struggled to understand the spontaneous separation of oil and water in a way that appealed to the electrostatic forces that she felt were responsible. She knew that “like dissolves like,” as she put it, but was unsure how to connect the heuristic with her knowledge of the relative strengths of intermolecular electrostatic interactions. Cleverly, she proposed that perhaps it was the greater length of the oil molecule in comparison to the water molecule that was responsible, so that while the pound-for-pound interaction strength between non-polar molecules might be weaker, the overall interaction between long oil molecules was sufficient to break up the water-oil interactions. When the interviewer points out that the water molecules might form a line having the same length as an oil molecule, Elena is troubled by the apparent inconsistency between her electrostatic knowledge and what she knows to be observably true:

(1) Interviewer: … And if the numbers came out that the water line was more attracted to the hydrocarbon line than two hydrocarbon lines were, would that bother you?
(2) Elena: That would bother me.
(3) Interviewer: Why would that bother you?
(4) Elena: Because then to me it would just seem like, well, why wouldn't water completely surround each individual hydrocarbon, if it overall has the stronger interaction than the hydrocarbon with the hydrocarbon?

Unable to press on using electrostatics alone, the interviewer points to an equation on the board relating free energy, enthalpy, and entropy ($\Delta G = \Delta H - T\Delta S$) and asks Elena to incorporate that relationship into her story.

(5) Interviewer: So in terms of this (points to $\Delta G = \Delta H - T\Delta S$ equation on whiteboard), what would the story be if the line of water is attracted more to the line of hydrocarbons [than are two hydrocarbon lines]?

(6) Elena: Ok, so, now this is where I kind of have two separate thoughts. Here (points toward the page with the oil and water task) we are talking about like electrostatic interactions...

(7) Interviewer: Where do those go (looking toward the board)?

(8) Elena: I just don't feel like they're involved in there (circling the equation with her hand) at all! So that's why I'm kind of having trouble piecing the two together in my mind.

(9) Interviewer: OK, gotcha.

(10) Elena: And I think that's also why that (quiz) question really confused me when [the Professors] brought up electrostatic interactions. Like I'm thinking entropy (points toward $\Delta G = \Delta H - T\Delta S$ equation on whiteboard) and you're thinking electrostatic interactions! How do those come together?

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.

(11) Interviewer: OK, but like what factors helped you to think about whether [the change in internal energy] was positive or negative? Like what were you thinking about to determine ΔH for the process of oil and water?

(12) Elena: Internal energy.

(13) Interviewer: And what did that… how did you figure out what sign that had?

(14) Elena: We were thinking, well is the internal energy changing? (thinks about it...) I honestly don't remember what we said... I feel like it was... positive?... Well, ok, so if you have interactions, you have bonds and you're breaking bonds and reforming them... I think that's where we got it from.

(15) Interviewer: Ok.

(16) Elena: So actually I guess the interactions, they're electrostatic interactions, so now it makes sense. (Laughs).

When she reasons that the intermolecular electrostatic interactions involved in bond breaking and bond formation help to 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 alone were to suggest otherwise.

(17) Interviewer: So, going back to... if we somehow looked up the numbers and found that a chain of waters was more attracted to a hydrocarbon chain than two hydrocarbon chains were [to each other], could you still tell the oil and water story?

> (18) Elena: I think so, 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 this (points to ΔS term) 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.... I feel like I can explain this so much better than I could have last semester. (Laughs).

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. During the interview, however, Elena uses her understanding of how the Gibbs free energy depends on enthalpic effects to begin the reconciliation process. By situating electrostatics within the enthalpy term of the Gibbs free energy expression, she connects for herself two realms that were previously distinct and unrelated, the “two separate thoughts” that she references in turn (6). Figure 5.4 shows the particular ideas that Elena has coordinated across the explanatory framework from Figure 5.1.

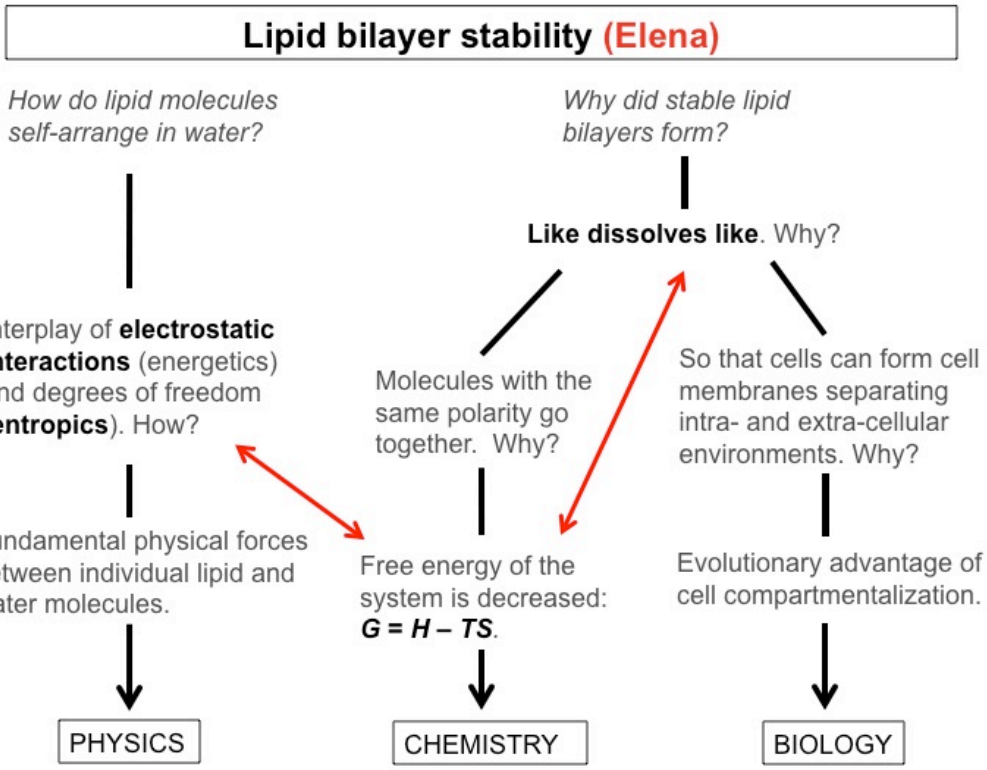


Figure 5.4. Elena coordinates her resources for thinking about lipid bilayer stability, locating her understanding of intermolecular electrostatic interactions within the Gibbs free energy relationship. Words in bold are Elena’s own. The other (plain text)

warrants and claims place her words within the context of possible explanatory silos related to lipid bilayer stability.

At the start of this episode, Elena is able to answer the question of why oil and water separate by referring to the phrase “like dissolves like.” What she would have struggled to do successfully is to answer the question, “*how* do oil and water separate?” Questions such as “how do oil and water separate?” were black-boxed in her prior biology and chemistry coursework to the extent that she was not aware of any contradiction in her thinking. By confronting a task that asked her to at once consider both her thermodynamic observations and her understanding of electrostatic physical principles, it was evident to her that boxes needed to be opened.

Much as Gavin expresses frustration in not being able to account for why particles move in the manner that they do during diffusion, Elena is initially bothered by her inability to account for the spontaneous separation of oil and water in terms of intermolecular interactions. For Gavin, resolution involves a description of Newtonian molecular collisions and how those collisions result in the spreading of particles. For Elena, resolution involves locating the competing effects of energy and entropy inside the Gibbs free energy relationship, and unpacking how that competition results in spontaneous behavior. This resolution allows Elena to say that “now it makes sense.” We will return to this comparison between the Gavin and Elena examples, and how *both* can be seen as worthwhile mechanistic accounts of biological phenomena, in Section 5.6.3.

Elena has found a way to locate her conceptual understanding of electrostatics within the expression that determines spontaneity in biochemical processes ($G = H - TS$). In this way, it is the *mathematical relationship* between free energy, enthalpy, and entropy that plays a central role in Elena’s interdisciplinary bridging. She associates the sign of ΔG with the spontaneity expressed by the biochemical heuristic, and identifies the internal energy within the enthalpy term as dependent on the relative strengths of intermolecular electrostatic interactions. The mathematical relationship provides a location for bringing together the “two separate thoughts” that Elena says were previously uncoordinated.

5.4.2 Using the Gibbs free energy expression, $G = H - TS$, to understand “work” in the context of enzymatic catalysis

Violet, another case-study student in NEXUS/Physics (Sawtelle & Turpen, 2014), uses the free energy expression as a bridge between her physical and biological conceptual resources for thinking about how enzymes function. In particular, Violet finds the IPLS course helpful in making sense of “work,” a term she had encountered in the context of enzymatic catalysis in her biology courses.

Enzymes catalyze (speed up) reactions by lowering the activation energy, often by bringing particular substrates into closer proximity or by positioning substrates into a particular orientation. Enzymes do not change the overall free energy change during a biological process, but they do catalyze such processes. As such, they alter the shape of the curve representing free energy as a function of reaction coordinate, even if they don't change the distance between the initial and final states on such a curve (Levine, 1978).

In an interview setting, Violet describes the bridging role the free energy relationship played in helping her to describe enzymatic activity:

> (1) Violet: You get this equation [$G = H - TS$] in chemistry and biology and now in this class. But you learn it from all different ways, all different angles, and I feel like in this class it's so much combined with biology that you have to put those two realms together… because in biology ΔG is how much free energy you have to do work in the system. And now in this class you actually have a specific definition of what work actually is, and instead of just like 'oh it can make this product,' you can see how an enzyme fits into what work is… I mean we haven't touched on that (in this course) but it's like, [when enzymes are] changing configurations… [that process] needs a force, so it coincides with it…
>
> (2) Interviewer: And so enzymes are connected with this equation in biology?
>
> (3) Violet: Yeah, I mean overall an enzyme is used to catalyze a specific reaction, and that specific reaction will have a ΔG that corresponds with it…

Violet notices that the enthalpy term in the free energy expression contains within it the $p\Delta V$ work done by the system ($\Delta H = \Delta U + p\Delta V$), and associates that $p\Delta V$ work with a force acting over a distance. Violet goes on to clarify how this definition of mechanical work helps her to make sense of enzymatic catalysis:

> (4) Interviewer: Now you feel like you have a more specific understanding of what? Work…?
>
> (5) Violet: Exactly. Because, when the enzymes come together, and they bring the products and the substrates together, they're interacting as that force that will like shove the two things together…
>
> (6) Interviewer: Ok.
>
> (7) Violet: So the reaction does occur more fast, and the enzyme, like in order to become active, needs to usually change its conformation… which can be equivalent to changing a displacement.

In turn (7), Violet makes a key connection between macromolecular conformational changes described in biology and chemistry courses and the general idea of displacement as described in IPLS. This connection allows her to relate the spontaneity of biological processes like enzymatic catalysis to fundamental definitions of mechanical work, and makes the physical underpinnings of the free energy expression relevant to her description of how catalysis happens.

Violet goes on to describe how enzymes catalyze chemical reactions by lowering the activation barrier in a free energy plot. She knows that enzymes accomplish this by bringing into contact various substrates involved in the reaction, but until identifying work as "force over distance" she has no resource for connecting the idea that enzymes "shove things together" with the idea that enzymes lower the activation barrier. Connecting these ideas requires both an association between free energy and work (an association that Violet makes by unpacking the free energy expression), and an association between work and the application of force over distance.

Violet identifies the notion of work as "force over a distance" as a physics idea, and identifies what she knows about enzymes and their function as coming from biology and chemistry. She coordinates these concepts through the free energy relationship in a way similar to Elena's use of the same expression to connect electrostatic interactions to the spontaneous formation of lipid bilayers. Where Elena locates electrostatic forces within the enthalpy term in the free energy relationship, Violet identifies forces (and the work they do) more broadly within that same term (Figure 5.5). Both the Elena and Violet examples point to the value in carefully framing the free energy relationship as an interdisciplinary bridge between physical and biological ideas.

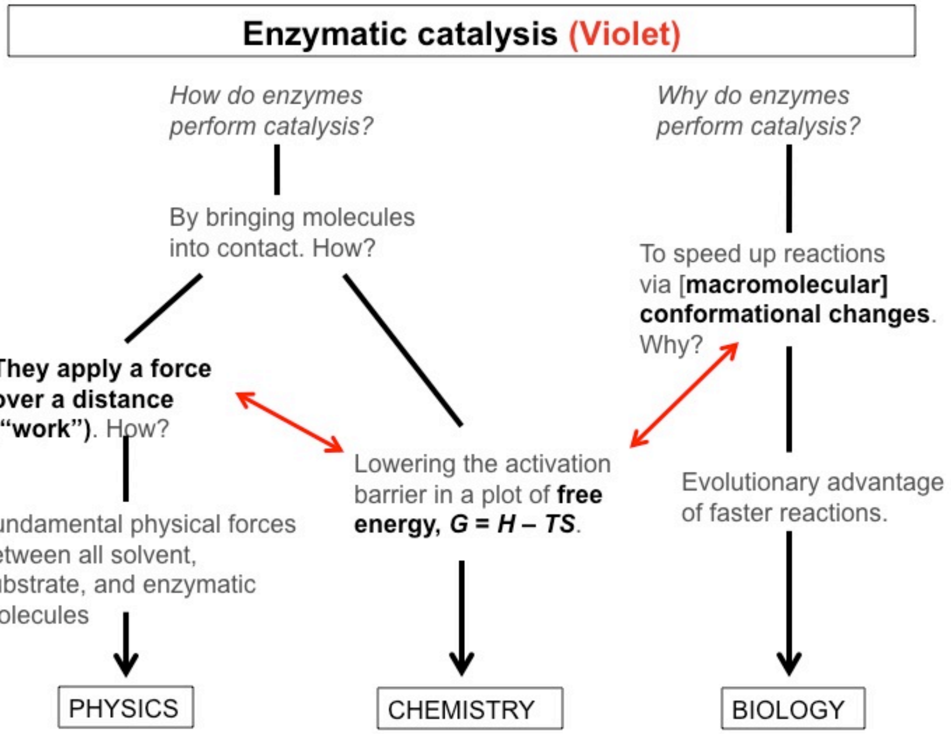


Figure 5.5. Violet coordinates her resources for thinking about enzymatic catalysis, relating the definition of work as force applied over a distance to free energy and the

biological function of enzymes. Words in bold are Violet's own. The other (plain text) warrants and claims place her words within the context of possible explanatory silos related to enzymatic catalysis.

Lipid bilayer formation and enzymatic catalysis are both "messy" biological processes for which detailed mechanistic accounts of the motions of individual particles are impractical. Nevertheless, we observe both Elena and Violet making meaningful interdisciplinary connections. Both Elena and Violet use the mathematical expression for Gibbs free energy to connect ideas from different disciplinary silos. The expression serves as a link between the spontaneity of biological processes (lipid bilayer formation and enzymatic catalysis, respectively), as represented by the sign of ΔG, and the physical factors that determine the enthalpy change ΔH during such processes (intermolecular electrostatic interactions and mechanical work, respectively).

5.5 Connecting mechanistic and functional explanations for biological phenomena

The Elena episode in Section 5.4.1 points to one way in which students might coordinate disciplinary ideas about a biological phenomenon like bilayer formation. In reflecting on the bilayer problem in an interview, Elena uses the expression for Gibbs free energy to link her understanding of biochemical spontaneity to what she knows to be true about the relative strengths of electrostatic interactions. A recitation exchange between two other NEXUS/Physics students, Hollis and Cindy, illustrates a second way in which the same biological context offers an opportunity for a different kind of interdisciplinary coordination.

Having worked through a two-week recitation exploring the qualitative role of energy and entropy in determining biological structure formation, the students are asked to consider why it is that lipids self-arrange into bilayer membranes rather than monolayers. Hollis attempts to position her group's physical explanation for bilayer stability alongside her own knowledge about the evolutionary favorability of such structures. She expresses to Cindy uncertainty that her physics understanding is consistent with her understanding of cell biology:

> (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 Gibbs 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 Gibbs 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).
(11) Cindy: Good.

Hollis' fist pump at the end of turn (10) conveys her feeling of resolution in having co-constructed (along with her groupmates) parallel physical and biological explanations for lipid bilayer formation.

This evolutionary advantage of compartmentalization and membrane transport is, for Hollis, the "biology explanation" for cell membrane formation. She says that lipid bilayers spontaneously self-assemble because such structures form semi-permeable barriers through which only certain molecules can pass. As Elena does, Hollis and her group associate the spontaneous formation of lipid bilayers with a negative change in free energy. Over the course of the recitation, they unpack the condition for spontaneity in terms of its energetic and entropic contributions. The explanation that results from the unpacking is, for Hollis, the "physics explanation."

In reality, Hollis' biology and physics explanations are not stemming from the same question. Her biology explanation in terms of cellular compartmentalization is functional, providing an answer to the evolutionary question, "Why are stable lipid bilayer structures used by living organisms?" Her physics explanation is an answer to the question, "How do lipid molecules self-arrange in water?" Hollis herself does not explicitly identify this distinction, but these questions are of course importantly different and call upon entirely different sets of resources. Figure 5.6 shows the particular ideas that Hollis has coordinated across the explanatory framework from Figure 5.2.

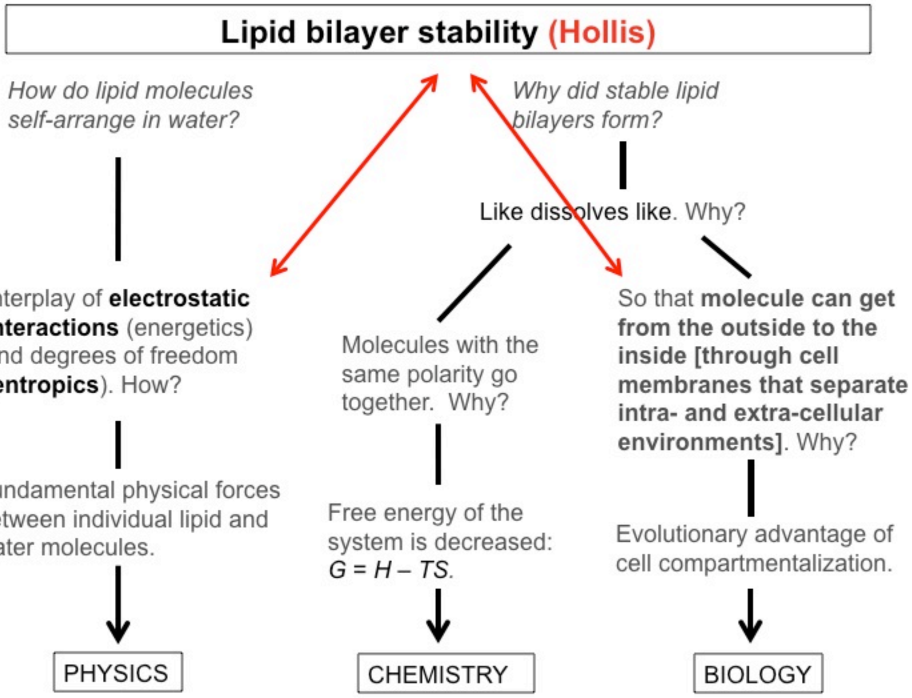


Figure 5.6. Hollis coordinates her resources for thinking about lipid bilayer formation. These resources include both a functional explanation for bilayers in terms of biological purpose, and an understanding of how the spontaneous formation of bilayers emerges from the interplay of energetic and entropic effects. Words in bold are Hollis' own. The other (plain text) warrants and claims place her words within the context of possible explanatory silos related to lipid bilayer stability.

The phenomenon itself – the stability of lipid bilayers – can be associated with many different types of questions. Some of these questions are "why" questions calling for functional or evolutionary accounts, while others are "how" questions calling for a physical account of how individual molecules form organized structures. Hollis is visibly satisfied that both the physics and biology "explanations" predict the same phenomenological result, the formation of stable lipid bilayers, as evidenced by her first pump and her assertion that Cindy had "explained it perfectly." Hollis has the expectation not only that both such explanations exist, but that both disciplines ought to play a role in describing the original *phenomenon*. She expects consistency across disciplinary accounts, and even if different disciplines might ask different questions, she expects that all disciplinary accounts should predict the same behavior.

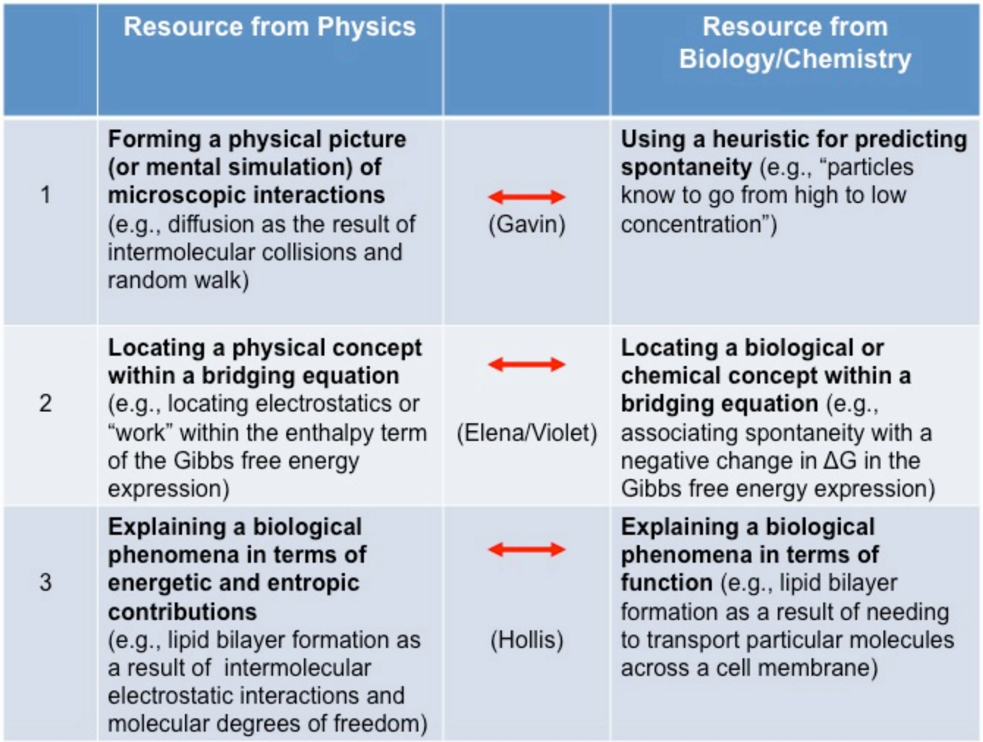
Whereas the Gavin and Elena examples in Sections 5.3 and 5.4.1, respectively, depict interdisciplinary connections between biochemical rules of thumb and more fundamental physical ideas, the Hollis example illustrates another way in which students cross disciplinary barriers in the NEXUS/Physics setting. While functional questions for which "evolutionary advantage" is an appropriate answer are primarily fleshed out in biology classrooms, the inclusion of authentic biological phenomena in NEXUS/Physics – and encouraging students to draw upon their knowledge of those other disciplines – affords students the opportunity to incorporate both fundamental molecular interactions and broad evolutionary principles into an interwoven network of resources for thinking about lipid bilayer formation.

5.6 Discussion

5.6.1 Three classes of interdisciplinary connections

In the preceding sections we have identified three ways in which students in NEXUS/Physics have crossed disciplinary boundaries in meaningful ways: by unpacking biochemical heuristics in terms of underlying physical mechanism (Gavin), by locating both biochemical and physical concepts within a bridging equation (Elena and Violet), and by coordinating functional and mechanistic explanations for the same biological phenomenon (Hollis). These classes form a basis that spans the space of interdisciplinary connections that we have observed over three years of teaching NEXUS/Physics, as will be discussed in Section 5.6.2.

The three classes of connections that we have identified can be mapped onto representations of explanatory silos related to different disciplinary treatments of biological phenomena (Figures 5.3, 5.4, 5.5, and 5.6). It is also possible to think of these classes more abstractly (without the context of any particular phenomenon) by viewing them as coordinating students' conceptual and epistemological resources from physics with those from biology or chemistry. Table 5.1 illustrates the resources that we see our students drawing on when making connections in our course.



	Resource from Physics		Resource from Biology/Chemistry
1	**Forming a physical picture (or mental simulation) of microscopic interactions** (e.g., diffusion as the result of intermolecular collisions and random walk)	↔ (Gavin)	**Using a heuristic for predicting spontaneity** (e.g., "particles know to go from high to low concentration")
2	**Locating a physical concept within a bridging equation** (e.g., locating electrostatics or "work" within the enthalpy term of the Gibbs free energy expression)	↔ (Elena/Violet)	**Locating a biological or chemical concept within a bridging equation** (e.g., associating spontaneity with a negative change in ΔG in the Gibbs free energy expression)
3	**Explaining a biological phenomena in terms of energetic and entropic contributions** (e.g., lipid bilayer formation as a result of intermolecular electrostatic interactions and molecular degrees of freedom)	↔ (Hollis)	**Explaining a biological phenomena in terms of function** (e.g., lipid bilayer formation as a result of needing to transport particular molecules across a cell membrane)

Table 5.1. Student resources for forming interdisciplinary connections in NEXUS/Physics are organized into three complementary classes. Each class is a row in the table. The names in parentheses refer to the case study students whose examples were used to exemplify the classes earlier in the chapter.

As we described in Section 5.4, Row 2 of Table 5.1 refers to those situations in which a mathematical expression (such as that for Gibbs free energy) serves as a focus at which students can link up their conceptual understanding from physics with their prior coursework in biology and chemistry. This sort of connection, unlike the connection identified in Row 1, does not require that a student have a detailed physical picture of every interaction involved in a process (see Section 5.6.3). Understanding where both physical and biological ideas "live" within the single mathematical expression is itself an instance of meaningful boundary crossing.

Not all mathematical relationships are created equal in their capacity to bridge physical and biological ideas. The Gibbs free energy relationship is an especially useful link between fundamental physical and biochemical ideas. This is partly due to the fact that the Gibbs free energy relationship can be seen as a proxy for the second law of thermodynamics (Schroeder, 2000; Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014), and that thermodynamics in general is a rich domain for interdisciplinary reasoning (Dreyfus B. , Geller, Meltzer, & Sawtelle, 2014). More specifically, life science students are comfortable associating Gibbs free energy with biochemical spontaneity (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014), while the enthalpy term ΔH contains within it internal energy and therefore all the forces typically discussed in introductory physics. In this way, the Gibbs free energy expression is an ideal link between biological and physical domains. Locating electrostatics or "work" within the enthalpy term requires, however, that one cross boundaries in which those topics are typically contained.

Other equations that appear in introductory physics ($F = ma$, for example) may not so naturally serve as bridging expressions. It is not that one could not in principle relate biological concepts to Newton's second law in a meaningful way. Rather, the fact that few biology courses describe phenomena in terms of fundamental Newtonian forces makes it difficult (though certainly not impossible) for life science students to imbue $F = ma$ with biological meaning. As all introductory science courses become more interdisciplinary in nature, an increasing number of expressions will serve as meaningful links.

Row 3 of Table 5.1 represents the idea that a student's overall understanding of a biological phenomenon is strengthened when he or she can coordinate between functional and mechanistic stories. Here, too, one's ability to leverage this connection requires a willingness in physics instructors to go beyond canonical conceptual and epistemological boundaries. A physics instructor need not place explicit emphasis on evolution and adaptive advantage to appreciate the added value that functional stories can provide. Affording life science students opportunities to consider biological function alongside physical mechanism helps them to strengthen the interdisciplinary explanatory fabric that supports their understanding of biological phenomena.

5.6.2 The landscape of interdisciplinary connections in NEXUS/Physics

We have identified three ways in which students have crossed disciplinary boundaries in meaningful ways, and have suggested that these approaches form a basis that "spans the space" of interdisciplinary connections in NEXUS/Physics. While it is not possible to prove that no instances of interdisciplinary sense making in our course (or other courses) fall outside the scope of these three classes, we argue in this section that these categories are representative of the types of connections we see students making throughout NEXUS/Physics. We begin by providing two examples in which the connections that students make might be thought of as a "linear combination" of these basis categories, a hybrid connection that draws upon more than one of the basis forms.

The first of these two examples of hybrid connections emerges from the discussion in NEXUS/Physics of the energy associated with chemical bonds (so-called "chemical energy"). In particular, explicit attention is given in our course to the commonly encountered description of adenosine triphosphate (ATP) as a "high-energy bond," a phrase used to signify that a large amount of energy can be released when ATP is hydrolyzed in an aqueous medium. The phrase "high-energy bond" is often incorrectly taken to mean that "bonds store energy," as if there is energy in the bond itself, waiting to escape when the bond is broken (Galley, 2004; Dreyfus, Sawtelle, Turpen, Gouvea, & Redish, 2014). Of course, this is not the case. Breaking a chemical bond does not release energy; it requires it. ATP can still be considered a "high-energy bond," but only if it is understood in the context of an aqueous environment, where bond reformation events do in fact release energy during the cellular process of ATP hydrolysis.

Dreyfus et al. (2014) explore how one student in NEXUS/Physics, Gregor, reconciles his understanding that breaking a chemical bond requires energy with his sense that energy is released during the ATP hydrolysis process. In an interview, Gregor describes how he answered a quiz question related to this apparent contradiction:

> *I put that when the bond's broken that's energy releasing. Even though I know, if I really think about it, that obviously that's not an energy-releasing mechanism. Because, you can't break a bond and release energy; you always need to put energy in, even if it's a really small amount of energy to break a bond… so I answered that it releases energy, but it releases energy because when an interaction with other molecules, like water, primarily, and then it creates an inorganic phosphate molecule that has a lot of resonance. And is much more stable than the original ATP molecule. So, in the end, it releases a lot of energy…"*

Gregor elaborates on this idea, identifying a difference between physics and biology in terms of the questions that each discipline is interested in answering about hydrolysis:

> *… I've just been taught for a long time that like ATP going to ADP equals like a release of energy. … I guess that's just the difference between physics and chemistry and biology. … Physic[ists] really love to think about things in vacuums, and without context, in a lot of senses. So, you just think about whatever small system you're—isolated system you're looking at, and I guess chemist or biologists thinking about more of an overall context…wherever a reaction or process is happening, that's important to what's going on.*

Gregor's statements during this interview indicate that he is drawing on two classes of interdisciplinary connections that we have described: (1) the unpacking of a biochemical heuristic in terms of physical interactions, and (2) the coordination of functional and mechanistic descriptions of biological phenomena.

Distinguishing the localized ATP bond-breaking event from the concurrent bond reformation events that occur during hydrolysis (and accounting for the energetic changes associated with each individual part of the process) is an example of unpacking a common biological heuristic device in terms of the physical interactions that underlie it. Gregor recognizes that the statement "ATP is a high-energy bond" is a heuristic that must be unpacked in terms of molecular interactions between the ATP molecule and its aqueous environment. The bond breaking event itself requires energy, while the concurrent bond reformation events with the surrounding water release energy, such that it is possible to see the entire process as one that releases energy even though the ATP molecule itself is stable. The heuristic "ATP is a high-energy bond" is only sensible when one carefully defines the physical system, and considers in detail the physical interactions between the system and its surroundings.

At the same time, Gregor also is coordinating his mechanistic understanding of ATP hydrolysis with a functional understanding of why bond breaking can lead to greater stability in a biological context. As Gregor puts it, breaking an ATP bond releases energy only if one considers the "interaction with other molecules, like water." Gregor understands that it makes sense to refer to ATP as a "high-energy bond" only when the molecule is considered in the context of the biological process of ATP hydrolysis. He says that energy is released during hydrolysis because it "creates an inorganic phosphate molecule that has a lot of resonance… and is much more stable than the original ATP molecule." Gregor brings biological stability into the story. He points out that, from a biological perspective, ATP bond breaking is meaningful only in the context of the aqueous cellular environment, where ATP has a function. In biology, "wherever a reaction or process is happening, that's important to what's going on." To detach a discussion of ATP hydrolysis from the functional role of ATP in the broader cellular environment (as Gregor sees physicists being interested in doing) would be to ignore the biological relevance of the hydrolysis process.

The interdisciplinary coordination that Gregor articulates in this interview draws stems from both (1) the unpacking of a biochemical heuristic in terms of physical interactions, and (2) the coordination of functional and mechanistic descriptions of biological phenomena. Function is not as explicit in the Gregor example as it is in Hollis' description of the "biological explanation" for lipid bilayer stability in Section 5.5, but it is present nonetheless. Gregor says that the biological description of ATP hydrolysis necessarily involves an aqueous environment in which a resonance-stabilized molecule forms, and in which the overall reaction (not just the bond breaking event) is important. In doing so, he is distinguishing questions that are of interest to biologists with those that are of interest to physicists, and he is pointing toward the coordination of functional and mechanistic accounts. By asking questions about ATP hydrolysis in NEXUS/Physics, we afforded Gregor the opportunity to see and articulate this connection, and thereby to make the discussion of chemical bond energy in our course relevant to processes in cellular biology.

A second example that illustrates the hybrid nature of interdisciplinary connections can be found in the Violet episode discussed in Section 5.4.2. We described how Violet used the free energy bridging expression to coordinate her understanding of work as a force applied over a displacement with her understanding of enzymatic catalysis. Like Gregor, however, Violet also alludes to a coordination between functional and mechanistic accounts. In describing how the free energy change ΔG is relevant for enzymatic activity, Violet says that "an enzyme is used to catalyze a specific reaction, and that specific reaction will have a ΔG that corresponds with it." She says that "the reaction does occur more fast, and the enzyme, in order to become active, needs to usually change its conformation."

Violet's descriptions involve terms that indicate she is thinking about the "use" of enzymes and the "need" of enzymes to change conformation in order to carry out its function. These are words related to biological function. Implicitly, Violet is coordinating her functional understanding of enzymatic activity with a mechanistic account of how that activity arises from molecular motions. She does not explicitly label the functional description as "biology" and the mechanistic description as "physics" in the way that Hollis does in Section 5.5, but this labeling would be consistent with her descriptions in Section 5.4.2.

The Gregor and Violet examples demonstrate how instances of disciplinary boundary-crossing in NEXUS/Physics can incorporate elements from more than one of the three classes of interdisciplinary connections represented in Table 5.1. The three rows in Table 5.1 represent the minimal number of categories needed to account for the space of interdisciplinary connections that we have observed. As mentioned in Section 5.2, we came to this classification after conducting 48 (approximately hour-long) interviews with 23 students during the first two year-long iterations of the course, and after filming weekly problem-solving sessions on a weekly basis. The 23 students that were interviewed represent more than 1/3 of the students enrolled in the course over two years. Of these 23 students, more than half explicitly referenced episodes that would exemplify one or more of the classes of connections summarized in Table 5.1. Most of these students referenced multiple episodes that would exemplify the classes. We have yet to identify episodes of interdisciplinary boundary-crossing in NEXUS/Physics that extend beyond some combination of the three classes. That said, our analysis here in no way precludes the possibility that life science students in our course or other IPLS courses might make connections in ways that are more naturally categorized differently.

5.6.3 Mechanism in interdisciplinary sense making

Implicit in the analysis throughout this chapter is the role of mechanistic reasoning in interdisciplinary sense making across biology, chemistry, and physics. It is worth taking a moment to articulate that role more explicitly, to identify the particular way in which mechanism appears in each of the classes of interdisciplinary boundary-crossing that we have identified. There is a tendency to view *only* the class of connections in Row 1 – the unpacking of heuristics in terms of detailed microscopic physical interactions – as mechanistic. We argue that the second class of connections – the use of mathematical expressions to bridge conceptual resources from biology and physics – is *also* mechanistic in nature, even when the analysis does not lead to a full picture of the microscopic physical interactions responsible for the phenomenon. In doing so, we adopt the idea that mechanistic explanation is characterized by the breaking apart of a complex phenomenon into component parts (Russ, Scherr, Hammer, & Mikeska, 2008)

Section 5.4.1 describes the lipid bilayer task, an activity designed to explore the energetic and entropic contributions to the spontaneous formation of cell membranes. In designing the lipid bilayer exercise, our goal is not for students to make direct connections between the biochemical heuristic ("like dissolves like") and the lowest turtles in the physics explanatory chain ("fundamental forces between individual lipid and water molecules"). The steps required to make such a connection would be prohibitively complex and context-dependent, depending in subtle ways on temperature, lipid concentration, and the length of the lipid hydrocarbon tails. A mechanistic description of bilayer formation that treats the individual lipid and water molecules as objects in an ornate free-body-diagram problem would require a computational approach, not an analytical one. We nevertheless view the connection that Elena makes in this moment as a meaningful marker of interdisciplinary sense making. Although she does not ultimately reach a description in terms of fundamental forces acting on fundamental particles, Elena's unpacking of the "like dissolves like" heuristic *is* mechanistic in the sense that she has described the overall spontaneous process in terms of its energetic and entropic components. This "breaking into parts" of a complex phenomenon, and the chaining of these parts together into a logical argument, is a hallmark of mechanistic reasoning (Russ, Scherr, Hammer, & Mikeska, 2008).

Elena may not come to a complete understanding of how fundamental electric forces push and pull individual lipid and water molecules into their stable bilayer arrangement. We would not expect her to do so. Since the goal in discussing bilayer formation in an IPLS course is to facilitate practice in identifying the qualitative roles played by energy and entropy in determining the spontaneity of authentic biological processes, an analytical approach that models the molecules as rigid, non-interacting spheres (or even as molecules interacting with, say, nearest neighbors) would not be appropriate. Such an idealized approach would render the problem biologically inauthentic and would require computational skills rarely encountered at the introductory level. At the same time, an approach that avoids authentic examples like bilayer formation entirely because full analytic accounts are not practical would fail to leverage resources that students have for thinking about energetic and entropic effects, and thereby fail to facilitate the meaningful interdisciplinary connection that Elena makes.

Connections that do not go to the lowest turtles in the explanatory chains – like the bridge that Elena draws between electrostatics and thermodynamics in Section 5.4.1 – might be called “middle turtle” connections. We view these middle turtle connections as an essential feature of interdisciplinary sense making, allowing one to take on rich biological phenomena without worrying that the “fully mechanistic” account in terms of fundamental interactions is too difficult. Recognizing the co-existence of two conceptual realms (electrostatics and thermodynamics) in the free energy bridging expression is itself an important step toward students seeing physics as a valuable tool for understanding the natural world.

The third class of connections described in this chapter – the coordination of functional explanations for biological phenomena with ones that unpack the energetic and entropic sources of those phenomena – draws attention to the idea that mechanistic reasoning can be valuably *supplemented* by accounts that focus on the evolutionary value of biological structures. Rather than avoiding explanations that rely on evolutionary advantage and functionality, this view of interdisciplinary sense making sees both mechanistic and functional explanations as dual pillars supporting a student’s overall understanding of particular biological phenomena.

5.6.4 Affect from interdisciplinary sense making

A number of objectives are routinely cited for designing introductory physics courses that are specifically tailored to life science students, including the increased importance of physical modeling and quantitative approaches in upper-division biology coursework, the need to train future physicians in methods and technologies developed in the physical sciences, and a general recognition that science disciplines are increasingly integrated and dependent on each other for inspiration and innovation . These objectives often align with national calls for substantial reform of the undergraduate curricula for life science and pre-health profession students (National Research Council (US), 2003; AAMC/HHMI, 2009).

In practice, instructors also recognize the importance of *affect* as both a mediator of participation in and an outcome of Introductory Physics for Life Scientists (IPLS) courses. Meeting the interdisciplinary objectives stated above seems to require that students be open to participating in physics. Because life science students often have negative orientations towards physics, helping these students come to “appreciate” or “like” physics is seen as an important component of interdisciplinary learning. This goal is sometimes made explicit, but more often is conveyed implicitly through efforts to include content that biologists would find “exciting” or of particular “interest.”

There are many reasons why life science students might profess to like or appreciate physics. Perhaps, for example, students see utilitarian value in their physics class such that their positive affect is tied to doing well in a course whose content knowledge will prove helpful on the MCAT exam or in later coursework (Elliot & Dweck, 1988; Grant & Dweck, 2003). Perhaps students like physics because they find it easy and it makes them feel competent or confident as a learner (Lent, et al., 2005). Perhaps students like physics because they find it intrinsically satisfying to make sense of why objects behave as they do. These different sources of positive affect can have consequences for how and if students participate in physics and potentially for their participation in other science disciplines. A better understanding of the sources of affective responses can help instructors be more intentional about the kinds of emotions they are trying to foster in their students, and about the association of these emotions with particular types of reasoning.

All of the examples presented in this chapter involve student satisfaction triggered by moments in which physics is helping a student *make sense* of phenomena previously encountered in his or her biology courses. These are moments in which students have made a connection that crosses disciplinary boundaries. It is not unreasonable to expect that some of this satisfaction is directly related to (and perhaps enhanced by) previous frustration in encountering the disciplines as disconnected. Gavin's reflection on his experiences in biology, for example, is accompanied by markers of frustration. He is exasperated that "in biology we never explain that," where "that" refers to the mechanism underlying a heuristic rule about diffusion. Likewise, we see Elena describe having "two separate thoughts" (one about electrostatics, and one about thermodynamics) between which she does not at first see any obvious bridge. We see Hollis struggle to find a "physics explanation" to accompany her "biology explanation" for membrane formation.

By identifying the types of explanatory coherence that generate positive affective response in our course, we hope to suggest ways of inviting life science students to participate in physics and see physical models as central tools for making sense of the biological world. In this sense, positive affective experiences around physics can be seen as a gateway to seeing common threads among science disciplines and appreciating the role of thinking and learning across disciplinary boundaries.

5.7 Conclusion

Research in science education emphasizes that the construction and understanding of scientific explanations is an important feature of learning science in the disciplines (Braaten & Windschitl, 2011; Craver, 2006; Bechtel & Abrahamsen, 2005). To explain is "to move beyond descriptions of observable natural phenomena into theoretical accounts of how phenomena unfold the way they do" (Braaten & Windschitl, 2011). This definition of explanation distinguishes "what" from "why," but does not distinguish between different disciplinary "why" questions. For example, it does not distinguish between an evolutionary account of the formation of biological structure and a mechanistic account of how that structure results from the interplay of energetic and entropic effects. While we might conclude that both of these accounts are "explanatory," they are different enough that our students sometimes struggle to form connections between them.

Explanation within a single discipline, let alone across disciplines, is controversial. Philosophers have debated the nature of explanation for decades, with little agreement (Nagel, 1979). Braaten and Windschitl (2011) describe five models of explanation that garnered particular attention in the 20th century philosophy of science literature, pointing out the pedagogical implications of each. One of these models, the “covering law” model, posits that natural events are explained by natural laws that “cover” those events. The Ideal Gas Law, for example, would be said to “cover” the specific ways in which the pressure, volume, and temperature of a gas relate. These covering laws generally provide a mathematical means for representing patterns in the natural world, but do not necessarily do so in a way that is easily adapted to varying contexts.

A number of philosophers have objected to the “covering law” model, arguing that (1) few such laws actually exist, and that (2) the laws express an explanatory commitment that often goes unacknowledged (Cartwright, 1997). Consider, for example, the “like dissolves like” heuristic used to describe the solubility of substances with varying polarity. The phrase “like dissolves like” does not explain solubility at an atomic or molecular level, but the phrase may still indicate explanatory commitments that are worth exploring, like the relationship between polarity and solubility. If an instructor adheres only to the “covering law” model of explanation, students are not encouraged to engage in reasoning beyond the basic application of the law, nor are they encouraged to explore the context-dependent (often discipline-dependent) nature of different kinds of explanations. As Schwab (1978) puts it, “intelligent and reliable application of principles requires us to have well in hand an understanding of the types of problems to which the principle is applicable and an understanding of the variations in application which are required for problems of different types.”

The “causal” model of explanation (Salmon, 1978) posits that explanations are most satisfying when they provide causal account. That is, explanations are more satisfying when theories and underlying mechanism are included along with the particular covering law. In this chapter we have added an additional layer by arguing that explanatory frameworks are especially satisfying when different disciplinary explanations are coordinated. We have seen that Gavin views physics as providing a causal account of diffusion that he did not encounter in his biology and chemistry coursework.

Two other models that have gained traction in the philosophy of science literature – the “pragmatics of explanation” and “explanatory unification view” – are particularly relevant to this chapter. The “pragmatics of explanation” model emphasizes that satisfactory explanation depends on context (Van Fraassen, 1980). As we have seen, different disciplines ask different questions, and those different questions suggest different explanatory pathways. As Schwab (1978) puts it, “different items of scientific knowledge are answers to different kinds of questions and the answer can hardly be said to be understood unless one knows the question to which it is an answer.” Our NEXUS/Physics students appreciate that different disciplines approach phenomena in different ways, sometimes explicitly distinguishing a “physics explanation” from a “biology explanation.” What counts as a “good” or “complete” explanation depends on the question being asked, and bridging disciplinary treatments of biological phenomena requires carefully distinguishing disciplinary objectives.

Those who posit the “explanatory unification view” (Friedman, 1974; Kitcher, 1989) argue that an essential feature of explanation involves unifying seemingly disconnected phenomena, thereby achieving some degree of global rather than local explanatory power. While this view of coherence motivates much of this thesis, and is most closely aligned with our own view of satisfactory explanation, we argue in the chapters that follow for a broader interpretation of unity.

We argue that unification does not only arise when different phenomena are coordinated within a single model or theory. Unification also arises in the context of a single phenomenon, when different explanations for that phenomenon are coordinated across disciplinary boundaries.

Coherence emerges not only by explaining a lot with a little, but also by connecting multiple explanations into a more integrated framework for understanding phenomena in the natural world.

Chapter 6: Sources of affect around interdisciplinary sense making[22]

6.1 Introduction: Different reasons for appreciating physics

In recent years, efforts have been made to design introductory physics courses that are specifically tailored to life science students (Meredith & Redish, 2013; Redish, et al., 2014; Thompson, Chmielewski, Gaines, Hrycyna, & LaCourse, 2013). A number of objectives are routinely cited for doing so, including the increased importance of physical modeling and quantitative approaches in upper-division biology coursework, the need to train future physicians in methods and technologies developed in the physical sciences, and a general recognition that science disciplines are increasingly integrated and dependent on each other for inspiration and innovation. These objectives often align with national calls for substantial reform of the undergraduate curricula for life science and pre-health profession students (AAMC/HHMI, 2009; National Research Council (US), 2003).

In practice, instructors recognize the importance of affect as both a mediator of participation in and an outcome of Introductory Physics for Life Scientists (IPLS) courses. Meeting the interdisciplinary objectives stated above seems to require that students be open to participating in physics. Because life science students often have negative orientations towards physics, helping life science students come to “appreciate” or “like” physics is seen as an important component of interdisciplinary learning. This goal is sometimes made explicit, but more often is conveyed implicitly through efforts to include content that biologists would find “exciting” or of particular “interest.” However, the sources and consequences of affective responses have not been well researched.

There are many reasons why life science students might profess to like or appreciate physics. Perhaps, for example, students see utilitarian value in their physics class such that their positive affect is tied to doing well in a course whose content knowledge will prove helpful on the MCAT exam or in later coursework (Elliot & Dweck, 1988; Grant & Dweck, 2003). Perhaps students like physics because they find it easy and it makes them feel competent or confident as a learner (Lent, et al., 2005). Perhaps students like physics because they find it intrinsically satisfying to make sense of why objects behave as they do. These different sources of positive affect can have consequences for how and if students participate in physics and potentially for their participation in other science disciplines. A better understanding of the pathways that lead to affective responses can help instructors be more intentional about the kinds of emotions they are trying to foster in their students.

The focus in this chapter is on affective responses that are triggered by moments in which physics is helping a student *make sense* of phenomena previously encountered in his biology courses by seeking coherent mechanistic accounts of these phenomena (Hammer, Russ, Mikeska, & Scherr, 2005). By focusing on how and why these moments of explanatory coherence generate positive affective response, we

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[22] This chapter is based on previously published material: Geller et al. (2014).

hope to suggest ways of inviting students to participate in physics and see physical models as central tools for making sense of the biological world. In this sense, positive affective experiences around physics can be seen as a gateway to seeing common threads among science disciplines and appreciating the role of thinking and learning across disciplinary boundaries.

In order to better understand both the sources and consequences of affective responses for participation and learning in science, we attend to interactions among affective displays and the ways in which students identify with and understand the epistemologies of the disciplines. In this chapter we present an episode from an interview conducted with "Gavin," a case-study student in an IPLS course. We examine how aspects of Gavin's identity interact with his epistemological orientation toward physics and biology to generate both positive and negative emotion, and unpack the *source* of his affect in these moments. In turn, we consider how this affective response influences and is shaped by epistemological views of coherence in the natural world.

6.2 Theoretical and methodological approach

In our analysis we attend to an instance in which positive and negative affect are coupled to sources of frustration and resolution. The unit of our analysis is not the individual but rather a series of moments in the context of this interview. We do not claim, for example, that Gavin *always* exhibits these particular emotions for the reasons illustrated by the episode we have chosen. Rather, the episode serves to highlight how Gavin's epistemic resources and ways of positioning his identity were coordinated in these moments. For reasons we describe below, these ways of coordinating epistemology and identity may influence Gavin in the future.

This framework views neither identity, nor epistemology, nor affect as stable entities that an individual carries with him from moment to moment. Instead, each of these dimensions is influenced by the different contexts in which an individual participates (Gupta, Danielak, & Elby, 2010; Hammer & Elby, 2002; Nasir & Saxe, 2003). This framework does not preclude the possibility that some of these constructs may be more or less consistently activated across a variety of contexts. It simply starts from the assumption that these constructs are sensitive to context and leaves the determination of whether they are more or less stable across context to empirical investigation.

Our focus is on the ways in which an interaction between *identity* and *disciplinary epistemology* is responsible for Gavin's *disciplinary affect* in an interview about his experiences in this IPLS course. Disciplinary epistemology here refers to ways of knowing and learning associated with a particular discipline (Hammer & Elby, 2003). For students, disciplinary epistemologies are likely to be closely tied to their course experiences (Watkins & Elby, 2013). For example, student might develop an understanding of biology as "complex and difficult to model in a simple way," or of physics as "abstract and idealized" from his biology and physics coursework respectively. Different course experience could contribute to the development of different sets of epistemological resources. That same student might develop an understanding of biology as describable in terms of elegant mathematical models or physics as uncertain and messy from another set of course experiences.

Identity, like epistemology, is dynamic and context dependent. As Esmonde (2009) puts it, "identities may shift in meaning or salience as one moves from one context to the next." The way a student positions herself relative to a discipline can also vary from moment to moment in more or less consistent ways. A student may over time begin to define herself as "a biology person," but may in other moments feel alienated from or excluded from that discipline (Nasir & Saxe, 2003), particularly in comparison to experts. Another student may identify as "someone for whom physics is really difficult," but may, at times, position herself as more aligned with the discipline (Sawtelle & Turpen, 2014). There may be ways of identifying that are broader than any particular discipline, but that interact with the individual disciplines in influential ways, such as one's view of himself as "a hands-on kind of person" or "a person who is good with symbols."

Epistemology, identity, and affect are related in various and nuanced ways. In Danielak et al. (Danielak, Gupta, & Elby, 2014), identity and personal epistemology are coupled such that a student identifies as a certain kind of knower. Disciplinary identity and disciplinary epistemology sometimes evolve together, as when researchers come to position themselves as aligned with or distant from particular disciplinary practices (Osbeck & Nersessian, 2010). Affect, in turn, can stabilize or destabilize epistemic orientations and aspects of identity or may result from a match or mismatch between them. Someone might feel anxious in a context in which his enacted identity is not valued, or proud and confident in a context where it is. At times these constructs of identity, epistemology, and affect reinforce each other, and at times they are in tension. This is particularly true in an interdisciplinary setting in which more than one set of disciplinary identities, epistemologies, and affective responses may be at work.

6.3 Gavin's Story: Satisfaction from a mechanistic explanation of diffusion

One goal of our IPLS course is to unpack the physical mechanisms underlying biological phenomena that are only described phenomenologically in typical introductory biology and chemistry courses. An example of this is the diffusion of particles or gases along a concentration gradient, a phenomenon with which life science students become familiar in their introductory biology and chemistry courses but for which they are often not provided a mechanistic explanation in those classes (Redish & Cooke, 2013; Dreyfus B. , Geller, Meltzer, & Sawtelle, 2014).

Gavin finds the unpacking of diffusion in mechanistic terms to be highly satisfying, and references the example in describing the role that our interdisciplinary course plays in his education more generally[23]:

> (1) Gavin: This [IPLS] class was very good about telling us about thermodynamics and entropy's role in the universe and why reactions proceed the way they do. And I think diffusion was when everything started to click; when we talked about how

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[23] In the transcript presented in this chapter, underlining indicates that emphasis was placed on that word. Body language and hand gestures are indicated with italics.

> 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 because the less they interact with each other the more stable their environment really was; there was less collisions and stuff like that. And pressure decreased. And so I felt like that's when things started to click [*snaps fingers*]... I was like that's why molecules go from higher concentration to lower concentration...
>
> (2) Interviewer: So you already knew that it happened?
>
> (3) Gavin: I knew that it happened but then I was like how the hell do they know where the lower concentration is?! 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. And that's why I struggle with [organic chemistry] so much, because it's like 'memorize the mechanisms and take the test' [*throws up his hands*]… well how the hell do I know why the mechanism is happening in the first place?!
>
> (4) Interviewer: How do the molecules know what to do...
>
> (5) Gavin: Exactly. And why do they do this bouncing thing [*moves hands back and forth*] and it was never explained to me very well, and then when I take this [IPLS] class and understand, oh, this is why molecules interact the way they do, this is why you are going to have this expansion of particles over space.
>
> (6) Interviewer: Yeah
>
> (7) Gavin: 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.
>
> (8) Interviewer: So it connected... you knew that it wanted the greatest entropy, and it connected sort of underneath it what was causing?
>
> (9) Gavin: Right it gave me a foundation...
>
> (10) Interviewer: And that was satisfying to you?
>
> (11) Gavin: 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.

In turn (3) of this exchange, Gavin reflects on his experience in prior biology (and organic chemistry) courses. He diagnoses biology as descriptive and fact-driven ("they have to go over so much stuff"), as placing too great of an emphasis on memorization of factual information and too little of an emphasis on the explication of "why things happen." Gavin's epistemological orientation toward biology in this moment is one in which he sees the discipline as failing to take up mechanistic explanations of the sort that his IPLS course provides for diffusion (or perhaps even failing to ask questions for which a mechanistic answer is appropriate). Gavin's reflection on his experiences in biology is accompanied by markers of frustration. He is exasperated that his biology instructors "don't really take time to explain why things happen" and that he is asked to "memorize the mechanism and take the test." In this moment both his words and hand gestures convey frustration. We describe Gavin's frustration as stemming from a disconnect between his identity as a sense-maker – "I am a why kind of person" – and what he finds to be an unsatisfying preoccupation with *knowing* (as opposed to *explaining*) in biology (left side of Figure 5.1).

Whereas Gavin's epistemological orientation toward biology is in tension with his identification as a "why kind of person," the epistemological view of physics that he articulates in this moment aligns with that identification. Gavin describes physics as a discipline where mechanistic sense-making is commonplace. In turn (1) he credits physics as a place where he came to understand "why reactions proceed the way they do," and in turn (5) as the place where he finally came to understand "why molecules interact the way they do… why you are going to have the expansion of particles over space." In turn (9) he labels the explanatory base he feels he acquired in physics as a "foundation." These descriptions of his epistemological orientation toward physics are accompanied by markers of positive emotion and excitement. He describes his IPLS course in turn (1) as the place where "everything started to click," and in turn (11) agrees with the interviewer that the conceptual foundation that he feels he established is "very satisfying." Where Gavin's epistemological orientation toward biology is in tension with his identification as a "why kind of person," his epistemological view of physics as a place where sense-making happens *aligns* with this identity in such a way that his affective response to physics is notably more positive (right side of Figure 6.1). Gavin also attributes his greater comfort on tests to improved facility with mechanistic explanation of the sort emphasized in his IPLS course, saying that such an understanding provides "the confidence in order to go into tests and be able to rationalize why things work the way they do."

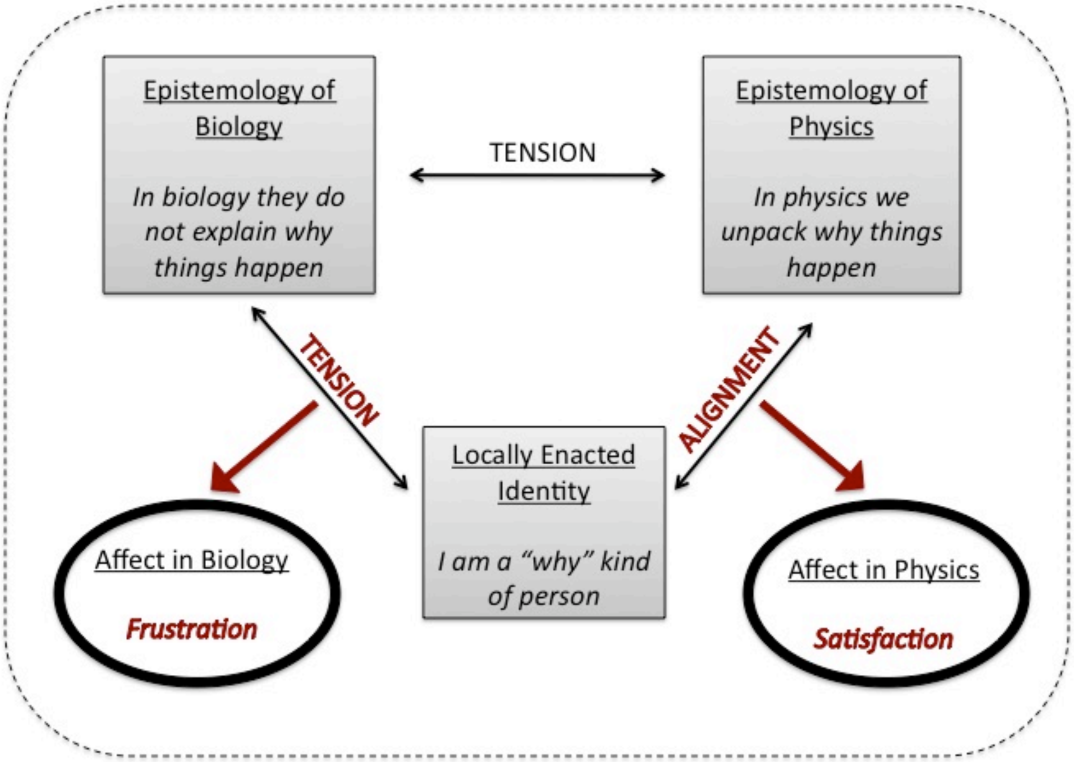

Figure 6.1. Modeling the sources of Gavin's affect during an interview in IPLS.

6.4 Implications for Interdisciplinarity

The frustration stemming from tension between Gavin's self-identification as a "why kind of person" and his epistemological view of biology is coupled to the satisfaction that Gavin achieves in his IPLS course. While we do not know if Gavin would or would not have appreciated physics in its own right had he not first encountered phenomena in biology for which he desired further explanation, his sense of resolution in IPLS *can* be attributed in part to his dissatisfaction with explanations in biology. Gavin positions his satisfaction with the role that physics is playing in his understanding of natural phenomena in direct *comparison with* and in direct *contrast to* his dissatisfaction with the incompleteness of explanations in biology.

Similarly, Gavin's frustration with the lack of attention to mechanistic explanation in his biology courses might actually serve to *strengthen* his ultimate sense of interdisciplinary connectedness and satisfaction. Because he sees *physics* class as a place where he was encouraged to develop explanations, Gavin may actually be more likely in the future to view physics as relevant and important for understanding the living world. The frustration that Gavin feels in association with biology may not only be productive in the sense that it enables him to more fully appreciate and experience the power of mechanistic explanation when he does eventually encounter it, but also in the sense that it allows him to appreciate a role that physics can play in the life sciences. A student who is never troubled by a lack of mechanistic reasoning in biology (or a student who sees biology as descriptive but actually *likes* that aspect of the discipline) might see superficial connections between biology and physics in an IPLS setting, but that student is less likely to see physical models as *essential* for answering some interesting questions in biology.

Figure 6.1 represents disciplinary affect as an *outcome* of the interaction (either tension or alignment) between identity and disciplinary epistemology. It is also plausible, however, that the alignment between Gavin's identification as a why kind of person and his disciplinary epistemology is *stabilized by* the positive emotions resulting from that alignment. The feelings may reinforce Gavin's belief that he is a sense-maker who values mechanistic explanation, and it is not unreasonable to predict that he may seek out opportunities in his future courses to do more of that sense making. We would hope, for example, that Gavin might begin to look for opportunities to make sense of biological phenomena in mechanistic ways that are authentic to the discipline of biology. Alternatively, if Gavin does not have this kind of opportunity in his subsequent life science courses, he might consider leaving biology for a field that he views as more conducive to mechanistic sense making (Danielak, Gupta, & Elby, 2014). By way of comparison, an IPLS student who experiences neither Gavin's frustration with biology nor his satisfaction in having explained something important in his physics course may be less likely to seek out connections between physics and biology beyond the confines of the IPLS environment.

In a course that has as one of its goals the dismantling of disciplinary silos, positive affect associated with the role that physics can play in unpacking biological phenomena is of particular importance. Future work is required to establish whether such affect indeed does stabilize a student's orientation toward interdisciplinary sense making, and to determine if such affect makes it more likely that that student will cross disciplinary boundaries in the future. But the positive affect is also an end *in and of itself*. Many prominent scientists have attributed their motivation to participate in science to those rare but powerful feelings of satisfaction, pleasure, and beauty that accompany the successful reconciliation of various pieces of conceptual understanding. It is possible for our students to experience similar satisfaction. When defining what it is that we hope our students will learn in interdisciplinary courses, we would be well served to consider also what we hope they might *feel* (Jaber, 2014; Pugh, 2011).

Chapter 7: NEXUS/Physics and the second law of thermodynamics: An interdisciplinary curricular thread[24]

7.1 The NEXUS/Physics course context

7.1.1 NEXUS/Physics life science students have resources for thinking about the second law of thermodynamics from biology and chemistry

The context for the curriculum presented in this chapter is the NEXUS/Physics course (Thompson, Chmielewski, Gaines, Hrycyna, & LaCourse, 2013; Redish, et al., 2014), an introductory course for life science students that leverages students' experiences in introductory biology and chemistry courses. Because our course has a year of biology and a semester of chemistry as prerequisites, our assignments and small group problem solving sessions leverage our students' familiarity with the material in those courses by introducing authentic biological problems from the beginning. Many students enrolled in NEXUS/Physics had not previously taken a chemistry course with an *explicit* focus on entropy and free energy. Despite this, our students report having seen these ideas in their introductory biology and chemistry courses, and report having used these ideas in meaningful ways (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014). In light of these reports, we see the second law thread as relevant to a wide range of Introductory Physics for Life Scientists (IPLS) courses, including ones in which students may not yet have had other courses that explore thermodynamics in depth.

This chapter argues that thinking of entropy as a link between energy and free energy, and in turn framing a discussion of the second law of thermodynamics in the context of considerations about free energy and spontaneity, can be an important step toward bridging different disciplinary treatments of thermodynamics. Meeting our life science students where they are means building upon the resources for thinking about free energy and spontaneity that IPLS students bring from their experiences in introductory biology and chemistry.

7.1.2 Students experience tension between disorder and biological structure

Students enter the NEXUS/Physics course with a variety of resources for thinking about entropy. Prior work has described a number of patterns in undergraduate students' thinking about both entropy (Sozbilir, 2003; Christensen, Meltzer, & Ogilvie, 2009; Bucy, Thompson, & Mountcastle, 2006) and spontaneity (Ribeiro, Costa Pereira, & Maskill, 1990; Sozbilir, 2004), but few attempts have been made to understand student thinking about entropy in biological contexts (Dreyfus B. , Geller, Meltzer, & Sawtelle, 2014). In the introductory biology textbook used by our students in NEXUS/Physics, entropy is defined simply as "a measure of disorder," with no more precise description or quantitative representation provided (Campbell, et al., 2008). The book notes only that "the more randomly arranged a collection of matter is, the greater its entropy," and that "there is an unstoppable trend toward randomization of the universe as a whole." The introductory chemistry textbook

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[24] This chapter is being prepared for submission to *Am J. Phys*.

assigned to our students in their general chemistry course introduces entropy in a similar way as the biology textbook, again defining entropy as a measure of disorder in a substance or system (Tro, 2011). We found that our students came to NEXUS/Physics with an understanding of entropy that was consistent with these descriptions (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014).

This idea of entropy as a measure of the disorder of a system was often in apparent tension with what our students knew to be true about the spontaneous formation of organized biological structures. Accounting for such organized biological structures against the backdrop of the ubiquitous "entropy as disorder" metaphor requires that we think carefully about how to connect ideas about entropy to ideas about spontaneity. It is worth emphasizing that *any* such treatment should take this tension seriously.

It is natural that IPLS students would feel tension between the second law of thermodynamics and what they know to be true about spontaneous cellular structure formation. While it may be technically sufficient to address the tension by asking students to think about the entropy of the system plus surroundings, rather than just the entropy of the system, it is an empirical question as to whether such an approach in and of itself best leverages student resources for thinking about spontaneity. It is also doubtful that one could reliably determine the sign of the entropy change for *either* the system or surroundings using *only* qualitative ideas about disorder. We have found that coordinating an approach that addresses the entropy of both system and surroundings with one that addresses the relationship between system free energy and spontaneity may in fact make use of student resources in a promising way (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014).

Given the imprecise definition of "disorder" and the variety of meanings students may associate with the word, there is no obvious reason to expect students to associate "disorder" with one particular meaning and not others. One way to resolve the tension between technical and colloquial uses of "disorder" and "chaos" would be to stop using those metaphors entirely when discussing the second law of thermodynamics. This approach, however, not only disregards the entrenchment of those terms in everyday understanding of entropy, but it ignores the highly productive ways in which students can leverage the terms. Approaches that suggest abandoning the use of metaphors like "disorder" entirely when talking about entropy do not consider the second law in an interdisciplinary context (Christensen, Meltzer, & Ogilvie, 2009). Life science students encounter the idea of disorder in their biology and chemistry courses, and sometimes use the idea productively.

We believe that refining the disorder metaphor and coordinating it with other formulations of entropy may be more effective than trying to eliminate it from our vernacular entirely. A theoretical commitment to leveraging student ideas means treating the disorder metaphor as a resource to incorporate, even if it is, in many cases, insufficient. As such, NEXUS/Physics approaches entropy from multiple perspectives. Both a canonical treatment in terms of probabilities and microstates and a treatment in terms of the spreading of energy over available degrees of freedom are presented in the hope that students will develop a set of coordinated resources for thinking about entropic phenomena. Both the microstate and "energy spreading" approaches are intended to more precisely define the "disorder" metaphor for entropy with which life science students are familiar (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014; Leff, 2012; Leff, 2007; Lambert, 2011). All these formulations are developed in broad terms on the "Why we need a second law of thermodynamics" link that is provided on the online page devoted to the NEXUS/Physics second law thread (NEXUS/Physics).

7.2 Overview of the NEXUS/Physics interdisciplinary second law thread

Having reviewed some of the issues that life science students bring to a study of the second law of thermodynamics in IPLS, we now describe in general terms the thread that links together the NEXUS/Physics readings, homework problems, and group problem-solving tasks (recitations) related to the second law of thermodynamics. This thread interacts with other curricular themes of the course that are described elsewhere (Dreyfus B. W., Geller, Gouvea, Sawtelle, Turpen, & Redish, 2014; Moore, Giannini, & Losert, 2014), and serves as a particularly useful setting for a series of tasks that emphasize the relevance of physics for understanding biological phenomena. The motivation for an interdisciplinary second law thread in NEXUS/Physics is two-fold: (1) to tie together into a coherent structure the concepts of diffusion, entropy, and free energy, and (2) to make connections across different disciplinary treatments of the second law. This latter objective stems from a commitment in NEXUS/Physics to teach material in a way that fosters interdisciplinary connections of the sort depicted in Chapter 5, and to draw upon students' second law resources from biology and chemistry of the sort described in Chapter 4. By doing so, we hope students come to see the second law of thermodynamics not just as an abstract constraint that physical systems obey, but as an essential tool in determining spontaneity in authentic biological contexts

Other organizational structures than the one presented here are possible for the second law thread. One might prefer, for example, to think of anything related to diffusion as a separate structure, existing as its own thread, and in fact different NEXUS/Physics instructors have taken notably different approaches to the second law curriculum. Our goal here is to provide a bird's-eye view of *one* particularly productive way in which the curriculum can be framed, one that places particular emphasis on aspects of the second law that cut across disciplinary boundaries.

7.2.1 The NEXUS/Physics second law thread: Gradient-driven processes

Life science students are familiar with the idea of spontaneity (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014). They have experience associating a spontaneous process with a negative change in a system's Gibbs free energy, and the NEXUS/Physics curriculum leverages this association in building intuition about the second law. In Section 7.3.2, we will describe what free energy is, and why Gibbs free energy is of particular importance in biological contexts. The overall goal of the second law curriculum can be seen as an effort to unpack in more detail what it means for a process to be spontaneous and what it means for the change in a system's Gibbs free energy to be negative. This central association between spontaneity and a negative change in Gibbs free energy thereby expands, through the tasks and problems encountered along the thread, to include associations with entropy and concentration gradients as well (Figure 7.1).

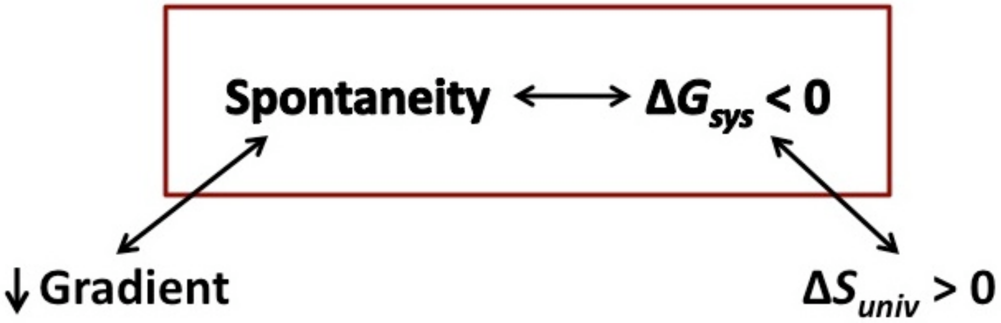

Figure 7.1. The NEXUS/Physics second law thread is built upon life science students' central intuition about the connection between spontaneity and a negative change in the Gibbs free energy of a system. Problems and tasks in the course develop an association between spontaneity and the diminishing of a physical gradient, and give students practice in unpacking Gibbs free energy in terms of its energetic and entropic components.

The gradient referenced in Figure 7.1 comes in many flavors, from concentration (the type of gradient that diminishes during diffusion or osmosis) to temperature (the kind of gradient that diminishes during thermal equilibration) to pressure (the kind of gradient that diminishes during the free expansion of a gas or the firing of a potato gun). Tasks and problems related to all of these types of gradients exist within the second law thread (see Section 7.4.1 below). Explicitly associating spontaneity with the decrease in a physical gradient highlights a common feature of otherwise disparate topics like diffusion and thermal equilibration. The idea of gradient-driven processes is thereby central to the second law thread, since processes of this sort indicate spontaneity and call for application of the second law.

7.2.2. The relationship of the second law thread to other NEXUS/Physics threads

The NEXUS/Physics second law thread is not designed to exist in a vacuum. It is conceptually tied up with other conceptual and epistemological threads in the course, and those other threads come in contact with the second law thread at multiple times (Figure 7.2).

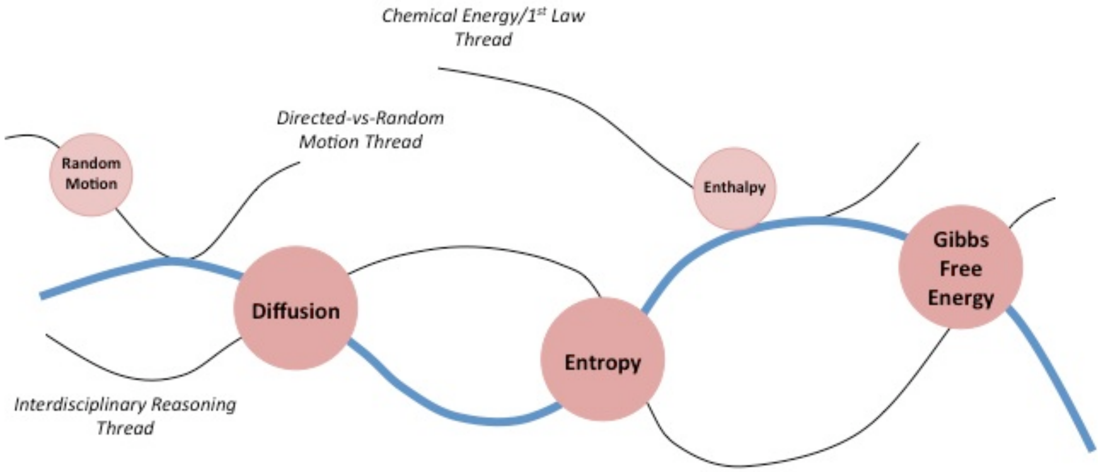

Figure 7.2. The NEXUS/Physics second law of thermodynamics curricular thread (blue) intersects the "Directed-vs-Random Motion" and "Chemical Energy/1st Law of Thermodynamics" curricular threads at various points. In addition, the "Interdisciplinary Reasoning" epistemological thread is closely intertwined with the second law thread, as it is with all of the curricular threads in the course. The details of the second law thread will be described in Sections 7.3 through 7.5 below.

In particular, random motion is the central *mechanism* by which diffusive processes occur. An understanding of how the random motion of individual particles can result in bulk movement during diffusive flow, i.e., an understanding of how random and directed motion are related, is essential for understanding why gradients spontaneously diminish. A link to the "Coherent vs. random motion" discussion is provided on the online page devoted to the NEXUS/Physics second law thread. Randomness is discussed in both the lecture and laboratory portions of NEXUS/Physics. An entire block of labs is devoted to studying the relationship between random and directed motion at the microscopic level (Moore, Giannini, & Losert, 2014), in the hopes that students will develop familiarity with both the mathematical and conceptual aspects of diffusion.

Not surprisingly, the first law of thermodynamics and issues related to chemical energy are intimately tied up with one's understanding of enthalpy and therefore one's understanding of Gibbs free energy. Indeed, it is probably most logical to conceive of enthalpy as existing within both the first and second law threads, since an interdisciplinary understanding of enthalpic change should be isolated from neither the first law discussion of chemical energy nor the second law discussion of entropy.[25] Likewise, the idea of thermal equilibration bridges the first and second laws of thermodynamics, exemplifying both energy conservation and the spontaneity of gradient-driven flow. A link to the "Energy: The Quantity of Motion"

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[25] It is of course possible to separate the discussion of enthalpy from the discussion of entropy. The point here is that, in an interdisciplinary environment in which the balance between enthalpy and entropy in determining spontaneity is central, that sort of separation is likely unproductive.

unit is provided on the online page devoted to the NEXUS/Physics second law thread (NEXUS/Physics).

In Sections 7.4 through 7.5, we describe in more detail the specific tasks and problems that strengthen the associations shown in Figure 7.1. In most cases, the details of each of the tasks are as not as important as the overall structure of the thread. Different but equally effective tasks could be constructed at each point along the thread, and instructors should feel free to modify and supplement the activities as appropriate. The problems and tasks discussed below are not comprehensive (additional materials can be found on the NEXUS/Physics online site) but provide useful examples of relevant exercises. In modifying or adapting the materials we describe, instructors should keep in mind that our central epistemological objective is to connect the physics that students are learning to resources that students bring to our course from biology and chemistry. Our tasks are designed with this goal in mind. To that end, although links for only the most current versions of tasks and exercises are provided on the NEXUS/Physics site, many were iteratively modified and reconsidered in light of student feedback (Gouvea, Sawtelle, Geller, & Turpen, 2013). Because ideas related to randomness and free energy are central to many of these second law tasks, we briefly describe these two concepts (in Section 7.3.1 and 7.3.2, respectively) before turning to a discussion of the tasks themselves.

7.3 The second law in interdisciplinary science

7.3.1. Random motion and the second law

Much of the conceptual material relevant to the underpinnings of randomness and diffusive motion exists within the "Coherent versus random motion" thread to which a link is provided on the NEXUS/Physics second law thread page (NEXUS/Physics). However, given that a number of the tasks mentioned in this chapter draw upon the connection between the random motion of individual particles and the spontaneous diffusion of groups of particles according to the second law of thermodynamics, we briefly review this conceptual foundation here. Diffusion is a central player in this discussion, both because of its importance in biological systems (Nilsson G. E., 2010; Evans & Von Caemerer, 2010) and because it is intuitive to students that things "want to go from high to low concentration" (Redish & Cooke, 2013; Geller, Gouvea, Sawtelle, & Turpen, 2014).

Within a fairly short amount of time of someone lighting a cigarette, everyone in the room can smell the smoke. Sometimes the molecules that are responsible for the smell are carried to us by the physical flow of the air that is moving – gentle breezes of convection. Sometimes, however, the air is still and the smell still gets to us. In this case, we say that the smoke has diffused from a region of the room in which it was highly concentrated to a region of room in which its concentration was initially low.

Diffusion is the process by which molecules move from regions where they are highly concentrated to regions where they are not as concentrated. While this phenomenon is easy to visualize, students are sometimes puzzled by the idea that a particular molecule "knows" to move from high to low concentration. And once they have diffused to fill the room, these particles seem to "know" not to all go back to where they started. Since the motion of molecules in a gas is random, on the surface this behavior seems peculiar.

At first glance, it is not entirely clear why the molecules do not re-coalesce in the corner of the room. After all, Newton's laws are symmetric with respect to time, such that we could replace "t" in any of our equations that describe the motion of a molecule with "$-t$" and still get the same physical laws and rules. It should not matter in which temporal direction a process proceeds. And yet, the example of cigarette smoke suggests that just the opposite is true, that there *is* a temporal asymmetry in the world.

The resolution, of course, stems from considering the bulk motion that results when many individual smoke particles undergo random walks. Even if each individual smoke particle moves randomly in response to the random collisions with nearby particles, the group of particles as a whole will spread to fill the space available to it. It is in this way that "directed" motion emerges from the "random" collisions between individual particles. Unidirectional, second law phenomena (like diffusion) are not inconsistent with the random motion of individual particles in the physical (including biological) world.

7.3.2. Free energy and the second law

An important reason for spending considerable time on entropy in an IPLS course is that it provides the link between energy as described in a typical physics course and free energy as described in a typical biology or chemistry course (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014). Consider the relationship between the Helmholtz free energy, the internal energy, and the entropy of a system:

$$F = U - TS$$

In biology and chemistry texts, it is often the free energy F (or, as we will see later, the Gibbs free energy G) that plays a central role, as the sign of the change in that quantity determines whether biochemical processes and reactions can occur spontaneously (Levine, 1978). In a typical introductory physics treatment of energy, some time is spent unpacking what goes into the internal energy term U in the above equation. A treatment of electrostatics, in particular, can be viewed through a thermodynamic lens as living inside the internal energy term in the expression for free energy. (Unfortunately, in a typical introductory course, "conservation of energy" and "the first law of thermodynamics" are usually taught separately, and electric potential energy is never explicitly connected to thermodynamics. Seeing electrostatics as living inside U requires a layer of interpretation not often apparent to our students.) The link between energy and free energy is entropy, and as the entropy of a system increases, less energy is "free" to do useful work (Levine, 1978).

To make the connections between energy, entropy, and free energy concrete, consider a standard idealized physics problem, the free expansion of a thermally isolated ideal gas (Figure 7.3).

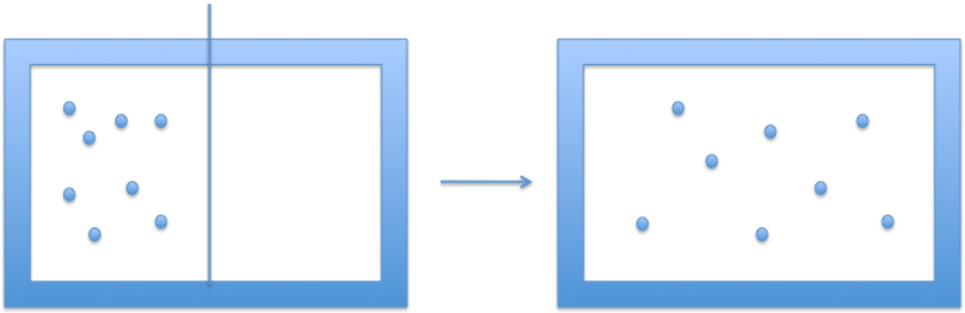


Figure 7.3. Free expansion of a thermally isolated ideal gas. When the barrier is removed, the gas expands to fill the available volume. The *energy* of the gas is constant during this isothermal free expansion, but the *free energy* of the gas decreases.

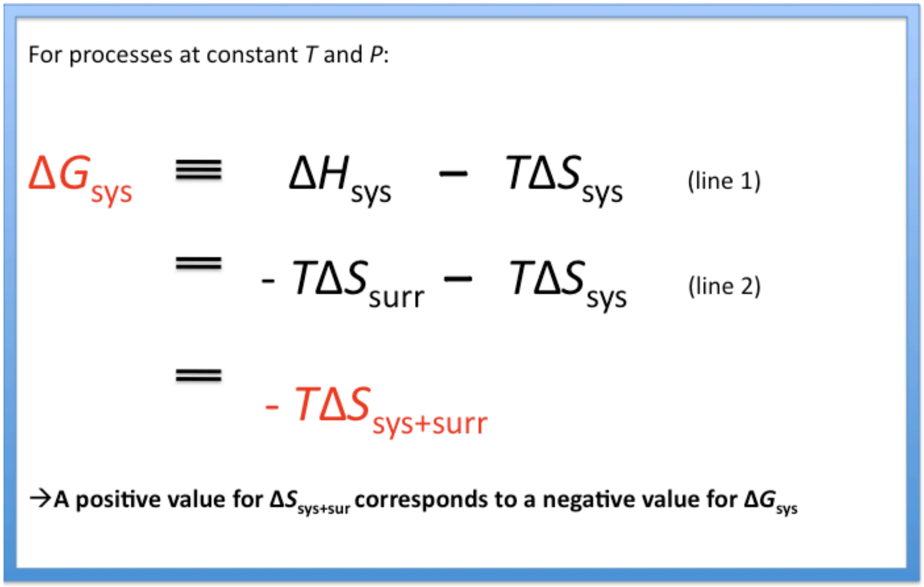
When the barrier is removed, the gas freely expands to fill the available volume. Since the compartment is thermally isolated from its surroundings, the internal energy *U* of the gas remains constant during the expansion, while the entropy of the gas increases. The result is that the freely expanded gas has the same energy but less *free* energy than the gas did before the barrier was removed. The expanded gas has less capacity to do work on its surroundings than the compressed gas did, which makes sense if we make the typical association between free energy and the capacity to perform useful work (Levine, 1978).

The second law of thermodynamics says that a physical process is spontaneous if it is associated with positive change in the overall entropy of the *system and its surroundings*. Use of this formulation of the second law to predict spontaneity is limited, however, by one's ability to account for all the entropy changes during a given process. Fortunately, under certain conditions one can re-write the second law such that spontaneity is determined by a property of the *system considered*, and not by a property of the system *plus* surroundings.

At constant temperature (*T*) and pressure (*P*), conditions common for biochemical processes, the system property that determines spontaneity is the Gibbs free energy. The Gibbs free energy differs from the Helmholtz free energy in that the former is a measure of the amount of chemical work that one can obtain from a thermodynamic system at constant *T* and *P*, whereas the latter measures the obtainable work when only *T* and *V* are constant (Schroeder, 2000). At fixed *T* and *P*, the Gibbs free energy can only change when the number of molecules of some species changes during some process. For this reason, the Gibbs free energy is of particular importance to chemists concerned with chemical reactions in which the number of molecules of one or more species changes.

The second law of thermodynamics can be equivalently written both as a statement about a system's free energy and as a statement about the entropy of the system and its surroundings. This equivalence is well positioned to play a central role in any treatment of the second law that leverages student ideas from biology and chemistry (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014). Figure 7.4

illustrates these parallel treatments, relating the entropy of the system plus surroundings and the Gibbs free energy of a system.



For processes at constant T and P:

$$\Delta G_{sys} \equiv \Delta H_{sys} - T\Delta S_{sys} \quad \text{(line 1)}$$

$$\equiv -T\Delta S_{surr} - T\Delta S_{sys} \quad \text{(line 2)}$$

$$\equiv -T\Delta S_{sys+surr}$$

→**A positive value for $\Delta S_{sys+sur}$ corresponds to a negative value for ΔG_{sys}**

Figure 7.4 For any process that occurs at constant temperature (T) and pressure (P), the Gibbs free energy of a system changes in a way that accounts for both the entropy change of the system plus surroundings. As such, the sign of the system's Gibbs free energy change during a process determines whether the process is spontaneous. Line 2 is equivalent to line 1 because the enthalpy change for a system at constant T and P, ΔH_{sys}, is equivalent to the heat transferred with the surroundings, $-T\Delta S_{surr}$. Schroeder (2000) provides more detailed relations between enthalpy, heat transfer, and $T\Delta S$.

When the entropy of the system plus surroundings increases during a process, the Gibbs free energy of the system decreases, and the process can proceed spontaneously. When the entropy of the system plus surroundings decreases during a process, the Gibbs free energy of the system increases, and the process does not spontaneously proceed.

The relationship between the system's Gibbs free energy change and the entropy change of the system plus surroundings suggests two possible ways of describing the second law. On the one hand, one might consider not just the entropy of the system, but also the entropy of the surroundings (line 2 in Figure 7.4). This approach requires that one have some way of measuring entropic changes not just in the local system one is investigating, but *everywhere*. In predicting the spontaneity of cell membrane formation in biology, for instance, one would not only need to measure the entropic changes for the lipid and water molecules in the membrane system, but also for everything else in the surroundings that was changed due to the process being considered. This is an approach to conceptual reconciliation that has been previously discussed in the literature (Toussaint & Schneider, 1998) and one that many physicists are familiar with employing when confronted with the question of how organized structures form.

A second approach to the second law is to consider the interplay of energetic and entropic effects on the *system itself* (line 1 in Figure 7.4). Our case-study interviews with students in NEXUS/Physics suggest that this approach may draw on students' experiences in biology and chemistry in particularly effective ways. Indeed, some introductory biology and chemistry textbooks *introduce* entropy by way of its contribution to the Gibbs free energy (Campbell, et al., 2008; Tro, 2011).

Life science students encounter enthalpy and entropy in the context of Gibbs free energy, through the equation $G = H - TS$, but they may not have experience unpacking the physical meaning of either of these constructs in any detail. Multiple tasks and problems along the second law thread encourage this unpacking (see Section 7.4.2 below). Entropy in particular is discussed from multiple perspectives, from a traditional physics account in terms of microstates and probabilities to an account that associates entropy with the "spreading" of energy over possible degrees of freedom. The latter approach has the advantage that the connection between the diminution of a physical gradient and an increase in entropy is more easily motivated.[26] Enthalpy, like entropy, is discussed in multiple contexts throughout the thread, particularly as a means for understanding the relationship between intermolecular energy and the spontaneity of biochemical processes (part of this occurs in content related to the first law of thermodynamics, as described below). By identifying the energy associated with intermolecular forces (electrostatic forces in particular) as part of the internal energy that contributes to enthalpy, one motivates why an enthalpy change depends on microscopic interactions.

7.4 Tasks along the NEXUS/Physics second law thread

7.4.1. Connecting spontaneity to gradient-driven processes

The section of the second law curricular thread that is addressed in this section is highlighted in Figure 7.5.

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[26] Note, however, that this energy spreading idea can activate or create a common misconception that the equilibrium (high entropy) state has the energy spread equally among all degrees of freedom. This is not correct. The state where all degrees of freedom have the same energy is a state of 0 entropy. It is only the average energy that is uniform. Fluctuations are essential for high entropy and the probability of different energies in a degree of freedom is given by the Boltzmann factor.

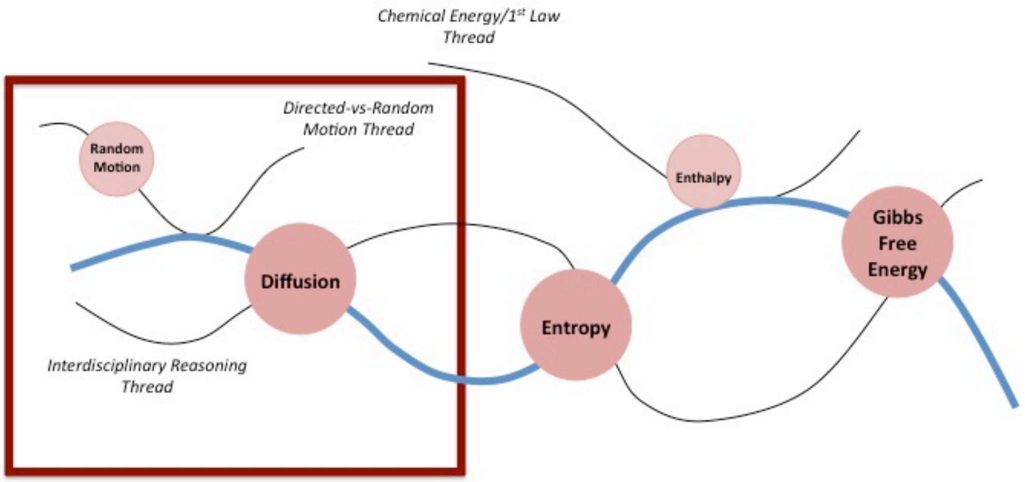

Figure 7.5. Section 7.4.1 describes the tasks, problems, and readings related to the highlighted portion of the second law thread. The activities are designed to foster an association between the diminishing of a gradient and the spontaneity of (bio)physical processes.

A number of readings, tasks, and prompts are aimed at fostering an association between spontaneity and the diminution of a physical gradient (see the left side of Figure 7.1). A series of in-class peer instruction and out-of-class homework problems provide students with experience in working with gradients of various sorts, especially those with biological significance. Links to the following tasks are provided on the online page devoted to the NEXUS/Physics second law thread (NEXUS/Physics):

- Random walk in 1D
- Random walk in 2D
- Linear diffusion in a gel
- Diffusion and viscosity
- Diffusion in time and space
- Diffusion/osmosis
- Cell polarization and activation

In addition, a recitation task entitled "1D Diffusion" is included in the Appendix.

Tasks designed to explore *thermal* equilibration can be found within the energy and first law of thermodynamics sections of the course, but it is valuable to bring those examples to bear in the discussion of second law gradient-driven processes. A temperature gradient spontaneously diminishes much as a concentration or pressure gradient does, resulting in an increase in entropy and decrease in Gibbs free energy.

The connection between spontaneity and gradient-driven processes have also been assessed on NEXUS/Physics exams. Links to the following exam prompts are provided on the online page devoted to the NEXUS/Physics second law thread (NEXUS/Physics):

- The macro micro connection
- Diffusion and slime molds
- Relay cells
- Random vs coherent motion (essay)
- Random vs coherent motion (Listeria)
- Random or not, here I come
- Growing root tips

Many of these exam prompts draw explicitly on material presented in the "Coherent vs random motion" thread (which, as shown in Figure 7.5, cannot be isolated from the second law thread). We include them here to draw attention to the connection between diffusive processes and the second law. Having students *repeatedly* interact with this connection reinforces the biological significance of the second law across a wide range of biological processes. Furthermore, as evidenced by the "The macro micro connection" essay question, unpacking the second law in these terms helps to explicitly connect the microscopic world of particle dynamics to the macroscopic world of thermodynamics.

7.4.2. Unpacking Gibbs free energy in terms of entropy and enthalpy

The section of the second law curricular thread that is addressed in this section is highlighted in Figure 7.6.

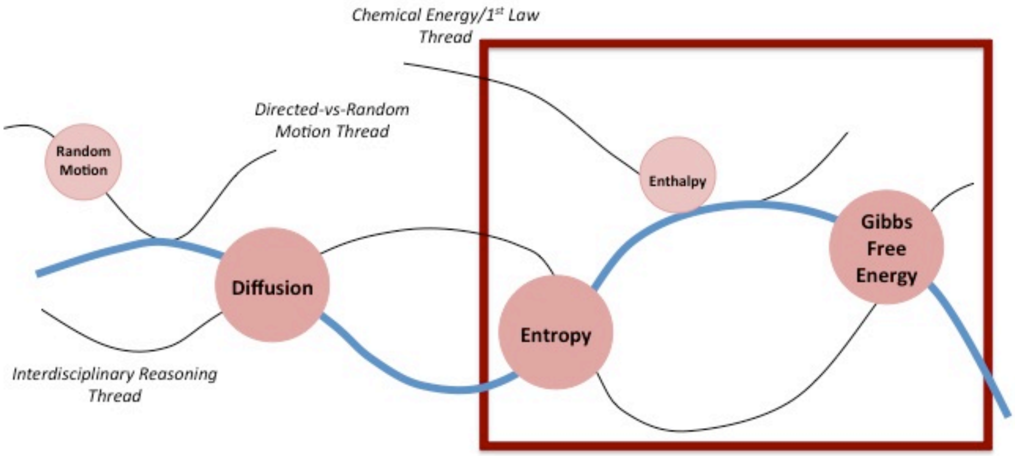

Figure 7.6. Section 7.4.2 describes the tasks, problems, and readings related to the highlighted portion of the second law thread. The activities are designed to unpack Gibbs free energy in terms of its energetic and entropic contributions.

Several in-class and out-of-class exercises are designed to provide students with practice in reasoning about entropy from a mathematical and probabilistic perspective. Links to the following tasks are provided on the online page devoted to the NEXUS/Physics second law thread (NEXUS/Physics).

- Flipping a coin – micro and macrostates
- Micro-macrostate
- Free expansion

In addition, at least two recitation sections were designed to develop student intuition about entropy as a measure of available microstates in real (bio)physical situations, and both of those are included in the Appendix:

- 1D Diffusion
- Polymers and Entropy

"1D Diffusion" (Appendix) examines particle random walk in one dimension, affording students the opportunity to *understand why* particles tend to spread out to fill the space available to them. The task asks students to make sense of the tendency for particles to go from high to low concentrations in terms of the collisions with nearby particles and a minimal amount of probabilistic reasoning. Students are prompted to extrapolate from the 1D diffusion example in order to prove that macrostates associated with a greater number of microstates are more likely, and to associate entropy with this measure. The spontaneous increase in entropy is seen as arising not just from an abstract "counting" of available states (as is emphasized in a traditional coin-flipping example) but from real microscopic physical interactions.

Although 1D diffusion nicely illustrates the connection between random microscopic interactions and the macroscopic increase in entropy, it does not do so in a context that draws on our students' resources from biology and chemistry. To provide an interesting biological perspective, "Polymers and Entropy" (Appendix) builds on a traditional coin-flipping counting task to introduce DNA configurational microstates. Treating DNA as a 1D polymer composed of many small links that have equal likelihood of orienting to the left or right, students determine the least and most likely polymer configurations. Like the coin-flipping and 1D diffusion examples, the DNA polymer exercise reinforces the idea that entropy increase is the result of probabilistic reasoning applied to molecular states.

The "1D diffusion" and "Polymers and Entropy" tasks treat entropy as a measure of the number of microstates associated with a system's macrostate. The "What is Free about Free Energy?" recitation (Appendix), on the other hand, asks students to explore the entropy increase of a freely expanding gas in terms of the spreading of energy over the degrees of freedom available to the gas. Although this context resembles one that would be encountered in traditional introductory physics courses (there is at least a superficial resemblance to the canonical "heat engine" context), the task is designed so as to begin the process of coordinating with more biological treatments of the second law. In particular, thinking of entropy in terms of the spreading of energy, rather than just as a measure of microstates, makes the connection of entropy to *free* energy more natural. This connection is of particular importance in a treatment of the second law that bridges biological, chemical, and physical applications of the law, given the central role that free energy plays in biology and chemistry courses. An entropy increase is associated with an increase in the amount of *degraded* (unusable) energy, and hence a decrease in the amount of *free* (usable) energy (Geller, Daane, & Sawtelle, 2013; Daane, Vokos, & Scherr, 2013; Daane, Vokos, & Scherr, 2014). The “What is Free about Free Energy?” task gives students an opportunity to explore these relationships.

Students were asked to describe the affordances and limitations of each of these formulations of entropy on a NEXUS/Physics exam (see the “Entropy formulations essay” on the online page devoted to the NEXUS/Physics second law thread (NEXUS/Physics)). We believe it is particularly valuable for students to reflect on these different formulations, so that the “disorder” metaphor for entropy that is emphasized in their biology and chemistry coursework can be coordinated with other approaches to entropy that are introduced in NEXUS/Physics.

Having spent time to develop intuitions around entropy, the second law thread incorporates problems and tasks designed to connect entropy to enthalpy via the Gibbs free energy expression, $G = H - TS$. Energetic (enthalpic) and entropic contributions to Gibbs free energy are considered alongside each other in the following set of in-class and out-of-class problems that can be found on the online page devoted to the NEXUS/Physics second law thread (NEXUS/Physics):

- Second law of Thermo Foundations
- Enthalpy, Entropy, Free Energy
- Evolution and the second law
- Evaporating a substance
- Spontaneous change

We saw in Chapter 4 that the free energy of a system – and in particular the way in which energetic and entropic effects determine the change in free energy of a system – plays a central role in our life science students’ understanding of thermodynamics. In one way or another, all of the students we discussed in Chapter 4 related their understanding of entropy to their understanding of energetic interactions between molecules and, in turn, to Gibbs free energy. The idea that spontaneity requires a negative change in the Gibbs free energy of the system served as a powerful resource for framing a discussion about what entropy can contribute to their understanding of biological phenomena. In fact, across all of our interviews with case-study students in Chapter 4, the notion that spontaneity requires a negative change in the Gibbs free energy of a system was one of the most consistently leveraged ideas, and was well coordinated with other elements of our students’ thermodynamic knowledge.

A treatment of spontaneity that emphasizes the interplay between energy and entropy is one for which an introductory physics course is naturally well suited. Unpacking the mechanistic underpinnings of entropy and enthalpy, the combination of which determines spontaneity in biological processes, is not always feasible in introductory biology and chemistry courses. IPLS courses can play an important role in encouraging students not just to *associate* spontaneity with a negative change in Gibbs free energy, but to understand *how* and *why* that negative sign emerges from energetic and entropic contributions.

The following three recitations in NEXUS/Physics are devoted to closely examining the relationship between enthalpy, entropy, and free energy, and all three are included in the Appendix:

- Salt Water

- Insane in the Membrane, Part I: Oil and Water
- Insane in the Membrane, Part II: Lipid Bilayers

The goal in each of these three tasks was two-fold: (1) to leverage our students' resources for thinking about free energy, and (2) to more carefully explore how a free energy change emerges from an interplay of energetic and entropic effects. While our life science students had strong intuitions for how to relate spontaneity to a negative change in Gibbs free energy, we wanted to ground the concept of free energy in specific, context-dependent energetic and entropic interactions. In "Salt Water" (Appendix), students are prompted to consider the enthalpic and entropic factors that contribute to the solubility of salt in water. The "Insane in the Membrane, Part I: Oil and Water" and "Insane in the Membrane, Part II: Lipid Bilayers" recitations (Appendix) prompt students to unpack in energetic and entropic terms the hydrophobic effect responsible for the spontaneous separation of oil and water and for the formation of lipid bilayer cell membranes in biology. The motivation for designing (and complications in implementing) the two-week task is described in detail in Geller et al. (2014). Several versions of these tasks were iteratively designed in light of feedback from students and our own evolving sense of the central role that free energy ought to play in our course.

The three NEXUS/Physics recitations that are devoted to examining the relationship between enthalpy, entropy, and free energy all involve "messy" biological contexts in which full mechanistic accounts of the movements of individual particles are not practical. As we described in Chapter 5, we believe that there is value in asking students to grapple with these biologically authentic contexts. The goal in discussing lipid bilayer formation in an IPLS course is to facilitate practice in identifying the qualitative roles played by energy and entropy in determining the spontaneity of authentic biological processes. As such, an approach that entirely avoids authentic examples like bilayer formation because full analytic accounts are not practical would fail to leverage resources that students have for thinking about energetic and entropic effects, and thereby fail to facilitate the meaningful interdisciplinary connections that our students make.

7.5 Capstone: Lipid bilayer formation

Life-science students have strong intuition about the relationship between spontaneity and Gibbs free energy. Sections 7.4.1 and 7.4.2 summarized our attempts in NEXUS/Physics to expand upon this central intuition, relating spontaneity to the decrease in various types of physical gradients (Section 7.4.1) and relating Gibbs free energy to entropy and enthalpy (Section 7.4.2). These connections can be summarized concisely: *the spontaneous diminution of a gradient is associated with an entropy increase for the universe or, equivalently, with the free energy decrease in a system*. This latter expression of the second law of thermodynamics in terms of a statement about free energy for a system is of particular importance in biological and chemical contexts, where the sign of the change in Gibbs free energy for a system is the primary indicator of spontaneity.

The "Insane in the Membrane, Part II: Lipid Bilayers" recitation task (Appendix) draws on all of these ideas in order to understand the spontaneous formation of the cell membrane (Reeves, 2012). Students identify electrostatic interactions between molecules and molecular degrees of freedom for both the lipid and water molecules in the system. In considering these factors alongside each other, students compare the energetic and entropic contributions to Gibbs free energy, and therefore to the spontaneity of the structure formation. An important implication of this analysis is that energetic considerations alone are insufficient for determining spontaneity in physical and biological systems.

Some of the students we interviewed in NEXUS/Physics expressed a belief that non-polar molecules come together in water because non-polar molecules are more strongly attracted to each other than they are to polar molecules. The heuristic "like dissolves like" was, for some students, explicable in terms of energetic considerations alone (Geller, Dreyfus, Gouvea, Sawtelle, Turpen, & Redish, 2014).[27] A primary goal of the lipid bilayer task is to give students an opportunity to explore the hydrophobic effect in an authentic biological context, and to see that its origins are in fact primarily entropic. An essay question on an exam following completion of the second law thread asked students to reconcile their understanding of relative intermolecular interaction strengths with their understanding that oil and water do spontaneously separate (see "Oil and Water Essay" on the online page devoted to the NEXUS/Physics second law thread).

Successfully responding to the oil and water essay prompt requires that students understand the relationship between energy, entropy, and the second law as expressed in terms of Gibbs free energy. More specifically, it requires that students distinguish *energy* from *free energy*, with the latter determining spontaneity. This question is similar in spirit to the ATP essay question that serves as a capstone to the chemical energy thread (Dreyfus, Gouvea, Geller, Sawtelle, Turpen, & Redish, 2014). As is true for the ATP essay, the lipid bilayer essay asks students to reconcile fundamental physical principles (electrostatics) with rules of thumb from biology and chemistry ("like dissolves like"). In doing so, we hope students come to see the second law of thermodynamics not just as an abstract constraint that physical systems obey, but as an essential tool in determining spontaneity in authentic biological contexts.

7.6 Conclusion

Figure 7.7 highlights some (but not all) of the tasks and problems along the NEXUS/Physics second law curricular thread.

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[27] Other students said that "like" molecules were more "attracted" to each other more than they were to "unlike" molecules, but did not explicitly mention energetic considerations.

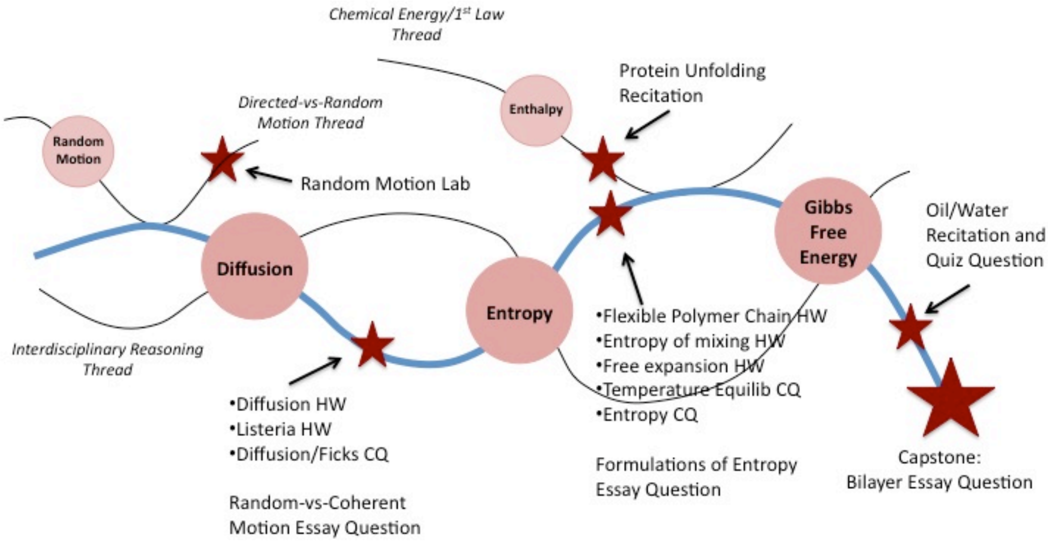

Figure 7.7. The NEXUS/Physics second law curricular thread, with selected tasks included for reference. The tasks can be found online on the NEXUS/Physics second law thread page.

We have argued that a coherent treatment of the second law of thermodynamics is important both in terms of the phenomena it allows life science students to understand and in terms of the disciplinary tensions it allows life science students to resolve. These tensions are visible in students' nascent understandings of the second law, as they seek to make sense of the apparent contradiction between the spontaneous formation of highly organized biological structures and a rule that says that disorder is always increasing in spontaneous processes. We have articulated a number of productive resources that students bring into our course context, and we should build from these resources in pursuing greater interdisciplinary coherence.

The NEXUS/Physics second law curricular thread reflects a treatment of entropy that emphasizes its role in determining the spontaneity of processes, including biological ones. Students develop intuitions for such spontaneity in their introductory biology and chemistry courses, and for the relation of spontaneity to the sign of the change in Gibbs free energy. In particular, students display an intuition that spontaneity depends on both energetic interactions and entropy, and an instinct to use sign of ΔG as a check on their analyses of entropy changes. We would be well served to leverage and refine these intuitions when introducing the second law of thermodynamics.

Unpacking the complex interplay between energy and entropy in determining the sign of the free energy change requires that we develop a set of illustrative and discussion-generating problems that help students understand these sometimes competing effects. We have described concrete example tasks which serve to illustrate the path forward that we propose, though much curriculum development is left to do. The burden for developing such curricula lies on the shoulders of *both* IPLS instructors and those teaching introductory biology and chemistry courses. The benefit of doing so is that our students will have opportunities to explore the thermodynamic world in a more coherent way.

Chapter 8: Conclusion

8.1 Summary of the central results of the thesis

This dissertation has depicted the nature of interdisciplinary coherence at the boundary of physics and biology. More specifically, we have explored interdisciplinary connections in the context of the second law of thermodynamics, a particularly rich topical area for understanding how student ideas are informed by disciplinary concepts, epistemologies, and attitudes. In this section (Section 8.1) we summarize the key findings from each of the central studies in the dissertation. These results are organized in sub-sections that parallel the four research questions identified in Chapter 3.2, and the most central aspects of these findings are in bold. In the section that follows (Section 8.2), we describe ways in which these findings are related to each other, and what education researchers not involved in IPLS efforts might learn from our results. We then describe the implications for instruction (Section 8.3) and some possible avenues of future research (Section 8.4). Finally, we discuss the importance of IPLS efforts in physics departments generally (Section 8.5).

8.1.1 Students' ideas about interdisciplinarity

In Chapter 1.2 we observed our life science students exhibiting a range of nuanced views about disciplinary relationships:

- **Students describe a hierarchical relationship in which disciplines are arranged by the spatial scale used to examine a particular system, or by the perceived complexity or level of abstraction associated with the disciplines.**

- **Students describe a desire to see physics embedded in a context that positions its relationship to biology via analogy, seeing the explication of such analogies as a particularly useful step toward an understanding of unfamiliar physics.**

- **Students reference ways in which general physical principles like energy conservation or entropy maximization impose constraints on biological systems.**

As we note in Chapter 1.2, the particular discipline-crossing resources that our students bring to bear is dependent on the nature of the problem being investigated and our student's sense of what constitutes a satisfying resolution in that moment. Indeed, most of the students we interviewed refer to more than one of the views mentioned in this section at one time or another during the case studies. Each view of disciplinary relationships comes with its own affordances, and adopting any single one of these views to the exclusion of others can be unsatisfying. Our students are likely to be most productive when they recognize different views of how the disciplines are connected, and can selectively bring to bear those different views at the appropriate moments.

8.1.2 Entropy, spontaneity, and Gibbs free energy in IPLS

In Chapter 4 we find that life science students develop a variety of resources for thinking about entropy and spontaneity in their introductory biology, chemistry, and physics courses. Helping students to develop a deeper and more coherent conceptual framework for organizing these varied ideas means attending carefully to the ways in which students interact with different disciplinary descriptions, and to the ways in which these descriptions may be in tension. Canonical introductory physics treatments of the second law of thermodynamics, while useful in some contexts, may not be the most productive ones in authentic biological or chemical contexts. **We argue in Chapter 4 that an approach to the second law of thermodynamics that emphasizes the interplay of energy and entropy in determining spontaneity (one that involves a central role for *free energy*) is one that draws on students' resources from biology and chemistry in particularly effective ways. We see the positioning of entropic arguments alongside energetic arguments in the determination of spontaneity as an important step toward making our life science students' biology, chemistry, and physics experiences more coherent.**

8.1.3 Classifying interdisciplinary gap-bridging in IPLS

In Chapter 5 we identify three ways in which students in NEXUS/Physics have crossed disciplinary boundaries in meaningful ways:

- **Students unpack biochemical heuristics in terms of underlying physical mechanisms**

- **Students locate both biochemical and physical concepts within a mathematical bridging equation**

- **Students coordinate functional and mechanistic explanations for the same biological phenomenon**

These classes form a basis that spans the space of interdisciplinary connections that we have observed over three years of teaching NEXUS/Physics. The three classes of connections that we have identified can be mapped onto representations of explanatory silos related to different disciplinary treatments of biological phenomena (Figures 5.3, 5.4, 5.5, and 5.6). It is also possible to think of these classes more abstractly (without the context of any particular phenomenon) by viewing them as coordinating students' conceptual and epistemological resources from physics with those from biology or chemistry. Table 5.1 illustrates the resources that we see our students drawing on when making connections in our course.

8.1.4 Sources of affect in interdisciplinary sense making

In Chapter 6 we unpack an episode in which a case study student in our course experiences positive and negative affect coupled to sources of frustration and satisfying resolution. **We argue that the positive affect that the student experiences stems from an alignment between his identification as a sense-maker and his epistemological view of this physics course as one that that values sense-making. Conversely, we attribute his frustration to a tension between his identity and his epistemological view of his biology courses as descriptive and fact-driven.** We discuss some implications of this model for students engaged in interdisciplinary sense-making more generally. In particular, we suggest that Gavin's frustration with the lack of attention to mechanism in his biology courses might ultimately serve to *strengthen* his sense of interdisciplinary connectedness and satisfaction. **We argue that affect is a worthwhile end in and of itself in interdisciplinary courses, and should not be viewed only as a *modulator* of student learning.**

8.2 Synthesis of the central results of the thesis

Sections 8.1.1 (summarizing Chapter 1.2) and 8.1.3 (Summarizing Chapter 5) suggest different ways of slicing our students' ideas about interdisciplinarity. As we mentioned in Chapter 3.2, these different slices are related to each other. For example, we describe in Chapter 1.2 that some students see physical laws as broadly "constraining" biological systems. By analogy, in Chapter 5 we see students use evolutionary advantage as a principle by which biological systems are constrained. In describing the general ways in which physics and biology are related for him, Wylie sees energy conservation as constraining biological systems (Chapter 1.2.3.3). On the other hand, Hollis sees the principles of evolution as constraining any physical account of bilayer formation (Chapter 5.5). In considering how students coordinate explanations from different disciplines, it is worth taking note of this bi-directionality. Anya's hierarchical picture of disciplinary relationships (Figure 1.1) is one that many practicing physicists adopt, but the episodes presented throughout this thesis suggest that such a picture fails to capture the full range of connections that life science students find meaningful.

The episodes presented in this thesis illustrate that students see the nature of explanation, and what counts as satisfactory explanation, as discipline-dependent. As mentioned in Chapter 2.3.2, explanation might broadly be defined as a movement "beyond descriptions of observable natural phenomena into theoretical accounts of how phenomena unfold the way they do" (Braaten & Windschitl, 2011). This definition of explanation distinguishes "what" from "why," but does not distinguish between different disciplinary "why" questions. It does not distinguish, for example, between an evolutionary account of the formation of biological structure and a mechanistic account of how that structure results from the interplay of energetic and entropic effects. While we might conclude that both of these accounts are "explanatory," they are different enough that our students sometimes struggle to form connections between them. When students do form connections between them, we have seen evidence that they find such coordination to be satisfying (Chapter 5.5). In research on interdisciplinary learning, and perhaps even in research on science education generally, it is worthwhile to acknowledge that different disciplines ask "why" questions in different ways. The interdisciplinary research in this thesis demonstrates that the nature of explanation is indeed context-dependent, a lesson that applies also to education research within a single discipline.

An essential feature of explanatory coherence is the unification of seemingly disconnected phenomena (Friedman, 1974; Kitcher, 1989). While this view of coherence motivates much of this thesis, the data presented in the preceding chapters supports a broader interpretation of unity. We have seen that unification does not only arise when *different phenomena* are coordinated within a single model or theory. Unification also arises in the context of a *single phenomenon*, when different explanation for that phenomenon are coordinated across disciplinary boundaries. The examples presented in Chapter 5 all support this broader view of unity. Coherence emerges not only by explaining (or "covering") a lot with a little (as, for example, Newton's laws do), but also by connecting multiple explanations into a more integrated framework for understanding particular phenomena in the natural world. Here again, there may be implications that go beyond the interdisciplinary learning environment. In seeking coherence within a single discipline, presenting multiple, well-coordinated avenues of explanation may be a productive approach.

A final theme that runs throughout the results presented in this thesis is the positioning of positive affect as a goal to be achieved by virtue of achieving coherence between different disciplinary accounts of biological phenomena. This positioning of affect as an end in and of itself, rather than as a mediator of learning, is worth considering even within the exploration of a single discipline. What, ultimately, is the goal of science education? We want our students to be prepared for the work force, of course, but most of us also want our students to achieve satisfaction in their lives.[28] While positive affect is often an implicit goal in science education generally, it is not common to talk explicitly about affect as and end point. As Pugh's work on transformative experiences makes clear (Pugh, 2011), the experience itself is a worthy goal of coherent education.

8.3 Instructional implications

Throughout this dissertation we have alluded to instructional implications of our findings. In this section we summarize those implications. Most of the remarks are aimed at physics instructors who would like to foster some amount of interdisciplinary learning at the boundary of biology and physics in their classrooms. Our remarks in this section are not directed only at physics instructors who are intent on teaching an entire IPLS course. Instructors in traditional algebra- or calculus-based introductory physics classes that are at least partially populated by life science students might benefit from these implications as well.

8.3.1 Teaching the second law of thermodynamics in IPLS

Chapter 4 argues that thinking of entropy as a link between energy and free energy, and in turn framing a classroom discussion of the second law of thermodynamics in

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[28] In fact, one might argue that the ultimate reason why we want students to achieve success in the work force is so that they (or the people they interact with) will achieve greater satisfaction in their lives.

the context of considerations about free energy and spontaneity, can be an important step toward bridging different disciplinary treatments of thermodynamics. Meeting our life science students where they are means building upon the resources for thinking about free energy and spontaneity that IPLS students bring from their experiences in those classes. Many students enrolled in NEXUS/Physics had not previously taken a chemistry course with an *explicit* focus on entropy and free energy. Despite this, our students report having seen these ideas in their introductory biology and chemistry courses, and report having used these ideas in meaningful ways. In light of these reports, we see the discussion in this thesis as relevant to instructors teaching a wide range of IPLS courses, including ones in which students may not yet have had other courses that explore thermodynamics in depth. Instructors in such courses should actively foster these conversations.

The life science students we describe in Chapter 4 have powerful resources for reasoning about spontaneity. We demonstrate how these ideas can be positioned relative to canonical statements of the second law, and point toward ways in which instructors might leverage these ideas in scaffolding tasks that support developing students' understanding. Our goal in Chapter 4 is *not* to offer a one-size-fits-all instructional approach to addressing the tensions described in that chapter. Such an approach does not likely exist. Rather, we discuss how our students' familiarity with free energy suggests one promising route toward bridging ideas about entropy and spontaneity, one that foregrounds a statement of the second law in terms of energetic and entropic changes in the *system*. Figure 4.3 is an especially useful reference for connecting canonical ideas with which physics instructors are familiar to ideas about enthalpy and free energy. We encourage instructors to make use of the equivalence depicted in that figure when teaching the second law in interdisciplinary environments. IPLS courses can play an especially important role in encouraging students not just to *associate* spontaneity with a negative change in Gibbs free energy, but to understand *how* and *why* that negative sign emerges from energetic and entropic contributions.

In designing tasks related to the second law of thermodynamics in our course, we do not assume that our job is to impart to students a set of canonical rules, nor do we ask students to abandon their initial set of ideas from biology and chemistry. Indeed, students enter our course with nuanced ideas about free energy and spontaneity, and the challenge is to craft tasks that build on these ideas and refine them. Because we listen to our students and observe how our tasks are taken up in the classroom, problem design in our course is invariably iterative. Student feedback plays an essential role in task design and re-design, and one must be willing to be led in unexpected directions by insightful student ideas. In teaching the second law in an IPLS environment, instructors must be particularly responsive to the ideas that students bring with them to the classroom from their work in biology and chemistry. This is perhaps the most important instructional implication of the entire NEXUS/Physics project.

We argue that a coherent treatment of the second law of thermodynamics in IPLS courses is important both in terms of the phenomena it allows students to understand and in terms of the tensions it allows students to resolve. These tensions are visible in students' nascent understandings of the second law, as they seek to make sense of (1) how technical and colloquial meanings of disorder are related, and (2) the apparent contradiction between the spontaneous formation of highly organized biological structures and a rule that says that disorder is always increasing in spontaneous processes. In Chapter 4 we articulate a number of productive resources that students bring into our course context, and we encourage instructors to build from these resources in pursuing resolutions to these tensions. This requires not just listening to students' ideas about the second law, but letting those ideas play a prominent role in what happens in class activities. Providing students with multiple sustained opportunities to bridge disciplinary ideas is an essential step toward resolving tensions that exist in students' ideas about the second law.

Unpacking the complex interplay between energy and entropy in determining the sign of the free energy change requires that we develop a set of illustrative and discussion-generating problems that help students understand these sometimes competing effects. In Chapters 4 and 7 we describe concrete example tasks that serve to illustrate the path forward that we propose, though much curriculum development is left to do. The burden for developing such curricula lies on the shoulders of *both* IPLS instructors and those teaching introductory biology and chemistry courses. The benefit of doing so is that our students will have opportunities to explore the thermodynamic world in a more coherent way.

8.3.2 Ways of fostering interdisciplinary connections

We note in Chapter 5 that not all mathematical relationships are created equal in their capacity to bridge physical and biological ideas. The Gibbs free energy relationship is an especially useful link between fundamental physical and biochemical ideas. This is partly due to the fact that the Gibbs free energy relationship can be seen as a proxy for the second law of thermodynamics, and that thermodynamics in general is a rich domain for interdisciplinary reasoning. More specifically, life science students are comfortable associating Gibbs free energy with biochemical spontaneity, while the enthalpy term ΔH contains within it internal energy and therefore all the forces typically discussed in introductory physics. In this way, the Gibbs free energy expression is an ideal link between biological and physical domains. Locating electrostatics or "work" within the enthalpy term requires, however, that one break silos in which those topics are typically isolated. We encourage instructors to "unpack" the enthalpy term in the Gibbs free energy expression, locating within it many of the concepts and topics that are normally covered in a traditional introductory physics classroom.

Other equations that appear in introductory physics ($F = ma$, for example) may not so naturally serve as bridging expressions. It is not that one could not in principle relate biological concepts to Newton's second law in a meaningful way. Rather, the fact that few biology courses describe phenomena in terms of fundamental Newtonian forces makes it difficult for life science students to imbue $F = ma$ with biological meaning. As all introductory science courses become more interdisciplinary in nature, an increasing number of expressions will serve as meaningful linkers, and instructors should look for such linkers as they develop curriculum for their courses.

We suggest in Chapter 5 that a student's overall understanding of a biological phenomenon is strengthened when he or she can coordinate between functional and mechanistic stories. Here, too, one's ability to leverage this connection requires a willingness in physics instructors to go beyond canonical conceptual and epistemological boundaries. A physics instructor need not place explicit emphasis on evolution and adaptive advantage to appreciate the added value that functional stories can provide. Affording life science students opportunities to consider biological function alongside physical mechanism helps them to strengthen the interdisciplinary explanatory fabric that supports their understanding of biological phenomena.

Implicit in the analysis in Chapter 5 is the role of mechanistic reasoning in interdisciplinary sense making. As we describe in Chapter 5, there is a tendency to view *only* one class of connections – the unpacking of heuristics in terms of detailed microscopic physical interactions – as mechanistic. We argue that a second class of connections – the use of mathematical expressions to bridge conceptual resources from biology and physics – is *also* mechanistic in nature, even when the analysis does not lead to a full picture of the microscopic physical interactions responsible for the phenomenon. Section 5.4.1 describes the lipid bilayer task, an activity designed to explore the energetic and entropic contributions to the spontaneous formation of cell membranes. In designing the lipid bilayer exercise, our goal is not for students to make direct connections between the biochemical heuristic ("like dissolves like") and the most fundamental warrant in the physics explanatory chain of claims and warrants ("fundamental forces between individual lipid and water molecules"). The steps required to make such a connection would depend on temperature, lipid concentration, and the length of the lipid hydrocarbon tails, making the analysis particularly complex and sensitive to small changes in context. Although a mechanistic description of bilayer formation would require a computational approach, we see the connection that Elena makes in this moment as an important example of interdisciplinary sense making.

Although she does not ultimately reach a description in terms of fundamental forces acting on fundamental particles, Elena's unpacking of the "like dissolves like" heuristic *is* mechanistic in the sense that she has described the overall spontaneous process in terms of its energetic and entropic components. This "breaking into parts" of a complex phenomenon is a hallmark of mechanistic reasoning. Elena may not articulate a complete understanding of how fundamental electric forces push and pull individual lipid and water molecules into their stable bilayer arrangement. We would not expect her to do so. Since our goal in discussing bilayer formation in an IPLS course is to facilitate practice in identifying the qualitative roles played by energy and entropy in determining the spontaneity of authentic biological processes, an analytical approach that models the molecules as rigid, non-interacting spheres (or even as molecules interacting with, say, nearest neighbors) would not be appropriate. Such an idealized approach would render the problem biologically inauthentic and would require computational skills rarely encountered at the introductory level. At the same time, an approach that avoids authentic examples like bilayer formation entirely because full analytic accounts are not practical would fail to leverage resources that students have for thinking about energetic and entropic effects, and thereby fail to facilitate the meaningful interdisciplinary connection that Elena makes.

Connections that do not go to the most foundational levels of the explanatory chains – like the bridge that Elena draws between electrostatics and thermodynamics in Section 5.4.1 – might be called "middle turtle" connections. We draw this name from our representation of how disciplinary explanations are related in NEXUS/Physics (Figure 8.1). As one moves down a given discipline's explanatory silo, answered questions become new questions themselves, such that each step in the explanatory chain is both a warrant (a justification) and a claim in need of further explanation (Bing & Redish, 2009; Bing & Redish, 2009a).

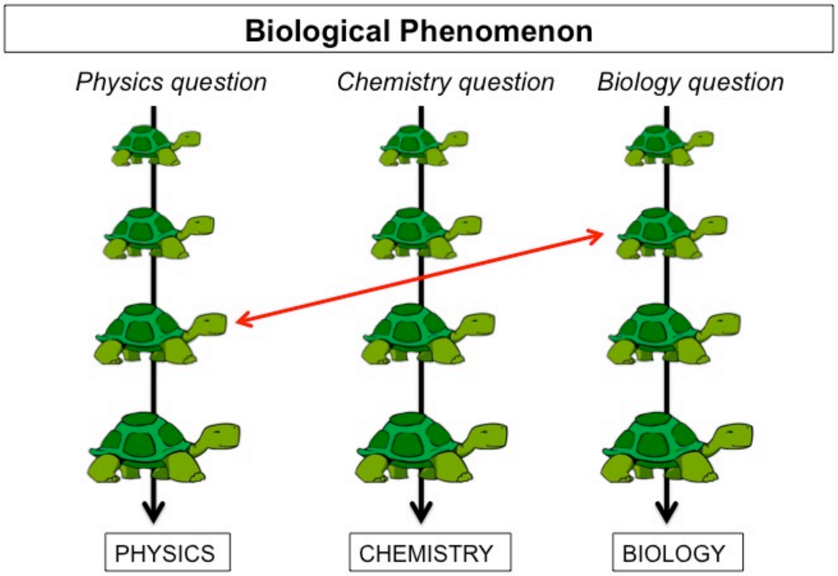

Figure 8.1. Explanatory silos. Answered questions become new claims in need of justification as one moves downward within an explanatory silo. Turtles are used in reference to the "turtles all the way down" expression of the infinite regress. The red arrows represent interdisciplinary connections made by students.

We view these middle turtle connections as an essential feature of interdisciplinary sense making, allowing both students and instructors to take on rich biological phenomena without worrying that the "fully mechanistic" account in terms of fundamental interactions is too difficult. Recognizing the co-existence of two conceptual realms (electrostatics and thermodynamics) in the free energy bridging expression is itself an important step toward students seeing physics as a valuable tool for understanding the natural world. Instructors should keep their eye out for opportunities to make "middle turtle" connections in their interdisciplinary courses.

8.3.3 Attending to affect

In practice, instructors generally recognize the importance of *affect* as both a mediator of participation in and an outcome of IPLS courses. Because life science students often have negative orientations towards physics, helping these students come to "appreciate" or "like" physics is seen as an important component of interdisciplinary learning. This goal is sometimes made explicit, but more often is conveyed implicitly through efforts to include content that biologists would find "exciting" or of particular "interest." Almost all of the examples presented in Chapter 5 involve student satisfaction triggered by moments in which physics is helping a student *make sense* of phenomena previously encountered in his or her biology courses. We encourage instructors to seek out more of these opportunities to use physical concepts to construct more satisfying explanations of familiar phenomena that are consequential in biological systems.

By identifying the types of explanatory coherence that generate positive affective response in our course, we hope in this dissertation to suggest ways by which instructors might invite life science students to participate in physics and see physical models as central tools for making sense of the biological world. In this sense, positive affective experiences around interdisciplinary sense making can be seen as a gateway to seeing common threads among science disciplines and appreciating the role of thinking and learning across disciplinary boundaries.

In a course that has as one of its goals the dismantling of disciplinary silos, positive affect associated with the role that physics can play in unpacking biological phenomena is of particular importance. Future work is required to establish whether such affect indeed does stabilize a student's orientation toward interdisciplinary sense making, and to determine if such affect makes it more likely that that student will cross disciplinary boundaries in the future. But the positive affect is also an end *in and of itself*. Many prominent scientists have attributed their motivation to participate in science to those rare but powerful feelings of satisfaction, pleasure, and beauty that accompany the successful reconciliation of various pieces of conceptual understanding (Einstein, 1982; Gopnik, Meltzoff, & Kuhl, 2009). It is possible for our students to experience similar satisfaction. When defining what it is that we hope our students will learn in interdisciplinary courses, we would be well served to consider also what we hope they might *feel*.

8.4 Future work

8.4.1 New contexts

The claims in this dissertation are grounded in the NEXUS/Physics environment. It is our belief that most of the results we have described will hold true when tested in other IPLS contexts. Few if any of the findings we have reported are inherently limited to the University of Maryland undergraduate population. Life science students across the country (at almost all types of institutions, from community colleges to research universities) are required to take introductory physics courses. While most of these physics courses do not currently have biology and chemistry as prerequisites, most life science students will have encountered much of the relevant biology and chemistry in high school (and many such students end up putting off physics until late in their undergraduate careers anyway). Employing the instructional strategies mentioned in the previous section of this chapter in these new environments will allow us to explore the generality of our claims. Is it easier to foster interdisciplinary coherence at smaller liberal arts colleges or on smaller two-year college campuses? Are the same approaches relevant in environments where students are more likely to go into health science fields other than medicine (physical therapy, dentistry, nutrition, etc.)? Our hope is that the work in this dissertation will directly contribute to the national effort to make life scientists' undergraduate experiences more coherent, in multiple environments and on multiple scales.

High schools are another important environment in which to introduce many of the interdisciplinary tools and strategies discussed in this thesis. The structure of interdisciplinary connections described in Chapter 5 need not apply only to post-secondary education. High school science curricula should be better integrated and should instill in young biology students the notion that physics, chemistry, and biology are all means by which to describe the living world.

The second law of thermodynamics in particular is seldom discussed in sufficient detail in high school science classes. Students are familiar with the everyday idea that energy is "wasted" and "used up," and with the need to "conserve it," but little effort is made to connect this type of energy (which is really *free* energy) to the canonical physics energy that is always conserved. A larger emphasis on the second law of thermodynamics in high school will go a long way toward bridging the usage of "energy" in a physics classroom with the usage of "energy" in everyday life. It will help students to answer the question of why we must conserve energy if all energy is always conserved.

8.4.2 Longitudinal work

A question that is not addressed in this dissertation is how a course like NEXUS/Physics impacts life science students' success in and appreciation for future biology coursework. Do life science students bring physics to bear in future biology and chemistry courses in different ways depending on whether their introductory physics course was tailored specifically for them? Do particular concepts or competencies from IPLS translate to upper division biology coursework more naturally than others? How do disciplinary epistemologies, attitudes, and affective responses help to mediate the transfer process as life science students move from introductory physics to the upper division biology environment? These questions are central to future research on the effectiveness of IPLS environments, and answering them requires longitudinal studies that track life science students over multiple years.

Longitudinal work may require a high degree of coordination among faculty from physics, chemistry, and biology. To follow introductory physics students into their chemistry and biology courses requires that faculty teaching each of those different classes all be part of the research process, and that there be sufficient overlap between the classes (in either content covered or skills assessed or both) such that it is reasonable to expect interdisciplinary transfer.[29] This sort of interaction between faculty from different disciplines can be seen as a fortunate byproduct of longitudinal interdisciplinary work. The more that faculty from physics, chemistry, and biology talk to each other, the more likely it is that life science students' experiences across different disciplinary classrooms will be coherent. The best way to achieve coordination among faculty from biology, chemistry, and physics is itself an interesting line of future research.

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[29] Even where such coordination among faculty is not possible, it would still be interesting to explore longitudinal work in order to understand where the existing system fails.

8.4.3 Ontological issues associated with free energy

Unique ontological issues accompany a discussion of free energy. While the substance or location metaphors for energy are often appropriate for discussions of energy generally, those metaphors may well be insufficient for describing the nature of free energy. The reason is that the free energy in a system involves gradients (see Ch. 7) in ways that other types of energy do not. In many ways, free energy is more ontologically similar to entropy than it is to energy – a confusing idea for introductory students just beginning to make sense of various forms of energy.

Consider, for example, an object at a temperature of 300K. If we place an object at 200K next to the first object, the system consisting of the 300K and 200K objects has a particular free energy. Now consider that, instead of placing a 200K object near a 300K object, we place a 100K object nearby a 400K object. Although the total energy in the (300K + 200K) system is the same as the total energy in the (400K + 100K) system, the free energy change as each system comes to equilibrium is not the same (nor can we say which object "has" the free energy). To see this most clearly, consider the free energy relationship $F = U - TS$. As each of the systems just described comes to equilibrium at 250K, the magnitude of the entropy increase will be greater in the case of the (400K + 100K) system than it is in the (300K + 200K) system, and therefore the free energy change during equilibration will be more negative for that system. It is in this sense that we can associate larger (negative) changes in free energy with larger initial gradients. Free energy is a *relational* construct, dependent not just on the kind of thing something is or where it is located, but also on the magnitude of the physical gradient that exists.

If we think of energy as a substance, it must be conserved. Free energy, however, is not conserved. Just as the entropy of the universe increases over time, the free energy in systems decreases over time. Because the term "free energy" implies a type of energy, students naturally expect it to be conserved. We have conducted interviews (not described in this thesis) that confirm the strength of this intuition for some students. The fact that free energy is not conserved comes as a surprise to these students, and this surprise raises important questions about how best to teach free energy from an ontological perspective. Christensen et al. (2009) have shown that students sometimes believe that entropy is a conserved quantity. We believe that future work will show that a similar misunderstanding applies to free energy.

We have collected data with Abigail Daane and the Physics Education Research Group at Seattle Pacific University that sheds light on these ontological issues associated with free energy. We have observed K-12 teachers interacting with free energy in ways that are consistent with what we see in our preliminary interviews with undergraduates in NEXUS/Physics. In particular, the teachers have a hard time conceptualizing that free energy is not a conserved quantity, since their instinct to associate "substance" with the word "energy" is strong. They describe a conviction that the loss in free energy observed somewhere must be accompanied by a gain in free energy someplace else, which of course is not the case. We intend to explore this ontological issue further in the near future.

8.5 The future of physics departments: a reason for physicists to care

The 20th century was marked by stunningly rapid progress in our understanding of the physical world. Advances in high-energy physics have allowed us to model the world of the very small in beautiful and deeply coherent ways, and advances in cosmology have allowed us to ponder the origin and fate of the universe in all its vastness. Quantum physics has not only changed our philosophical view of nature and our role as observers, but it has paved the way for the extraordinary advances in computational technology that will define the century ahead. Time Magazine rightly named Albert Einstein the person of the 20th century because it was a century defined by extraordinary developments in physics (Golden, 1999).

Life exists somewhere in between these realms of the very small and the very large, and the 21st century will be defined by advances in this richly nuanced intermediate arena. The 21st century will be one in which the scientific advancements that most dramatically change our lives will live at the intersection of physics and biology. Advances in nanotechnology will interact with advances in synthetic biology in remarkable ways, changing the way we think about life and its place in the universe. The current generation of undergraduates does not remember a world in which daily and social life could be understood independently of computers, and the next generation may not remember a time in which people did not know their genetic make-up just as well as they knew their email addresses. As these biological breakthroughs filter their way to the general consciousness, students will continue to gravitate toward the life sciences. Already we see campuses having to accommodate vast numbers of students who want to study biology, and this trend shows no signs of slowing in the years ahead. Physics will remain relevant only insofar as it serves a new generation of students that is more curious than ever about the living world.

Physics is a beautiful subject, one worthy of study regardless of what relevance it might have for the life sciences. But the reality is that students will not be drawn to it, nor will they be required to study it, unless it bears directly on their understanding of biology. The relevance of physics departments in the 21st century will depend largely on the ability of such departments to adapt to this new reality. Solutions to some of the most important biological problems that exist today call for the types of models and quantitative approaches that have defined the physical sciences for centuries. Physicists would be well-served to embrace this important new role, rather than to resist it.

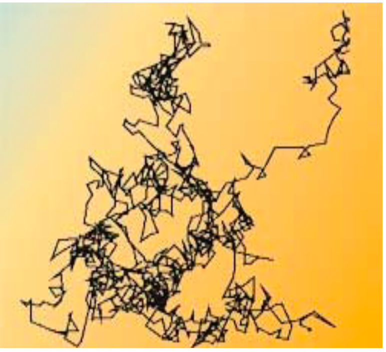
The boundaries between physics and biology have blurred in recent years, and they will only get blurrier in the years ahead. The primary motivation for physics faculty to embrace this new reality ought to be that we owe it to our life science students to meet them where they are, and to foster a coordination between physics and their interests in biology. If that motivation is insufficient, one should keep in mind that the very existence of large physics departments is increasingly dependent on the decision of biology departments to require that their students take introductory physics. If the courses we offer their students ignore the essential role that physics plays in understanding biological systems, it is unlikely that introductory physics will remain a central prerequisite for a career in the life sciences. In turn, fewer physics faculty will be necessary, and fewer students will have the chance to experience the subject we love to teach.

Appendix: Selected recitation tasks

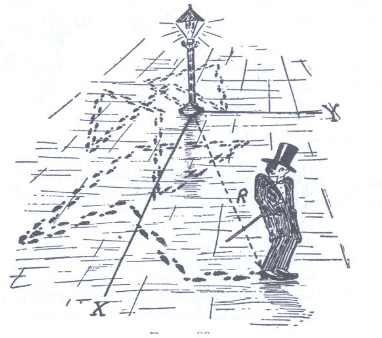
Recitation Task: 1D Diffusion

***Central Question*:**

Most of us have the intuition that a group of molecules located in the center of a room will spontaneously diffuse from their starting position until eventually they are distributed throughout the space that they have available to them.



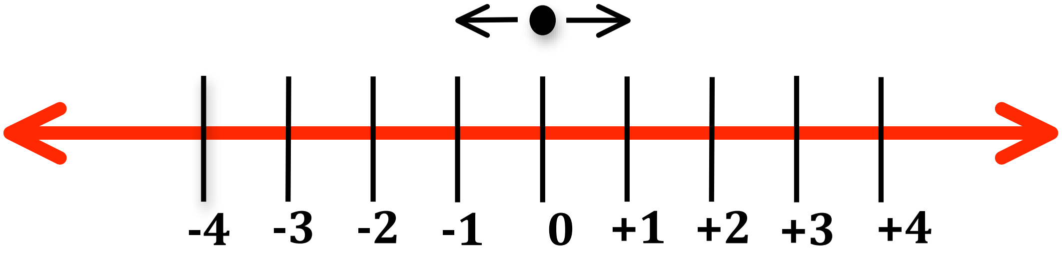
But why does this happen? *How can we show that it is more likely for the molecules to spread out than to remain bunched up in the center of the room? That's what we will try to answer in this recitation.*



Part I. Following a Single Molecule

Let's explore what happens to a molecule that is jostled randomly by neighboring molecules in a cellular environment. Imagine that we have a whole bunch of molecules, but that we are able to paint a black dot on one of them, and follow this black-dotted molecule around.

Suppose for simplicity that such a black-dotted molecule is located at $x = 0$ and confined to move along one dimension. Let's call that dimension the x-axis (see Figure below). Because this molecule experiences random collisions with nearby molecules, it has an equal chance of moving a step to the left to $x = -1$, moving a step to the right to $x = +1$, or staying put at $x = 0$. The probability of each of these events happening is 1/3. Each step that the molecule takes obeys these rules.



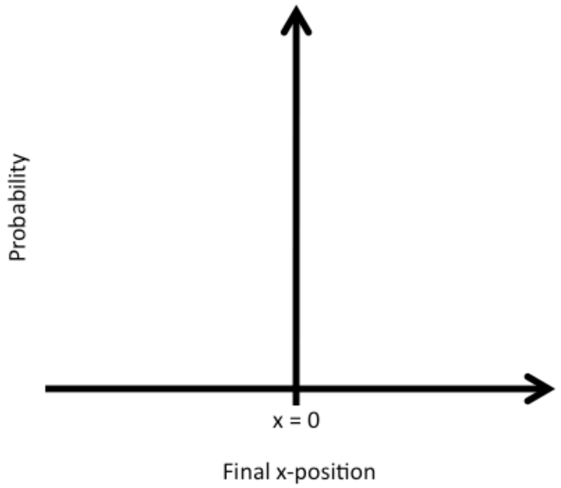
Prompt 1. After the molecule undergoes 2 steps, determine the probability that it ends up at (a) $x = 0$, (b) $x = +1$, (c) $x = -1$, (d) $x = +2$, and (e) $x = -2$.

Prompt 2. After the molecule undergoes 3 steps, determine the probability that it ends up at (a) $x = 0$, (b) $x = +1$, (c) $x = -1$, (d) $x = +2$, and (e) $x = -2$.

Prompt 3. Fill in the following table. For each final position, determine how many possible paths the molecule could take to get there given a particular number of steps.

Final Position	Number of Possible Paths			
	1 step	2 steps	3 steps	4 steps
x = +4				
x = +3				
x = +2				
x = +1				
x = 0				
x = -1				
x = -2				
x = -3				
x = -4				

Prompt 4. Plot the probability (you can use Excel if you like, or just sketch the plots by hand) of a molecule arriving at a particular position along the *x*-axis after *N* steps (axes for these plots shown below), where $N = 1, 2, 3$, and 4. That is, create four plots on the same set of axes (one for $N = 1$, one for $N = 2$, one for $N = 3$, and one for $N = 4$). Label each plot with its *N* value.



Prompt 5. Use your plots to describe what happens to the probability of finding the molecule at different positions along the *x*-axis as the number of steps increases. What would happen as the number of steps *N* got really large?

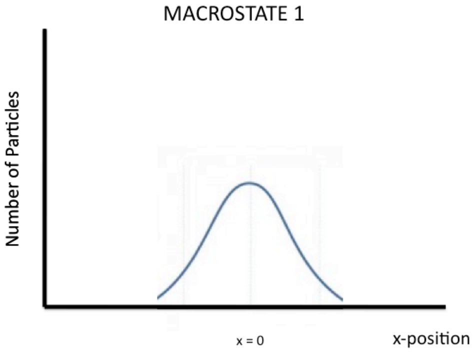
Prompt 6. Why is the probability of finding the molecule at *x* = 0 greater than the probability of finding the molecule at some other value of *x*, after any number of steps *N*?

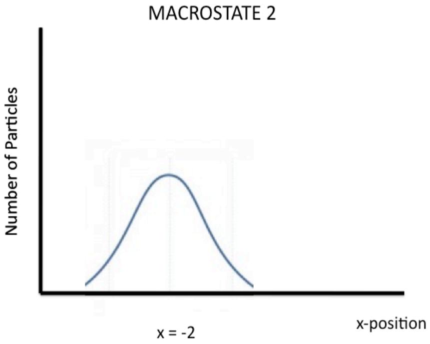
Part II. Many Particles: Microstates, Macrostates, and Entropy

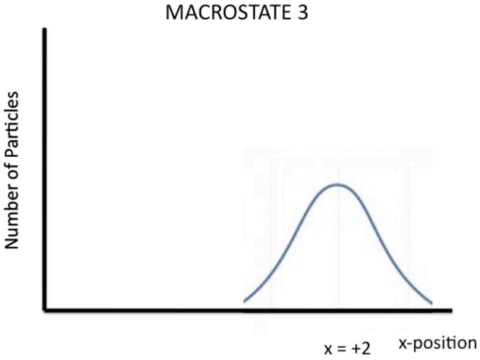
The assumption in Part I was that we were following around a single molecule as it was jostled by nearby molecules. Now let's consider what would happen if we had a system consisting of a LOT of identical molecules located initially at *x* = 0, each undergoing 1D random walks. Suppose we could follow all of them.

In this scenario, a *microstate* of the system specifies the particular position on the x-axis of every single particle at a particular time. A *macrostate* of the system specifies only *how many* particles end up at each position along the x-axis at a particular time (say, 4 particles at *x* = -1, 3 particles at *x* = 0, 7 particles at x = +1, etc) but does not specify *which* specific particles end up where. *Make sure you understand this distinction*! A particular macrostate can be represented by a plot showing how many particles exist at each position along the x-axis at a particular time *t*.

Three example macrostates for this system (all particles at *x* = 0 at *t* = 0) are shown here for some time *t*:







Prompt 6. Rank the macrostates shown above from the most probable to the least probable. *Use what you found in Part I of this recitation to justify your ranking in terms of the number of microstates associated with each macrostate.*

Prompt 7. Suppose that the system is in MACROSTATE 1 (shown above) at some initial time *t*. Explain why the curve representing the system's macrostate flattens and spreads as time goes on.

Prompt 8. Entropy is a measure of the number of microstates associated with a particular macrostate. Explain, using microstate and macrostate language, why the diffusion of particles away from their initial position at $x = 0$ is accompanied by an increase in the entropy of the system.

Recitation Task: Polymers and Entropy

One way of understanding entropy is to say that since a system with random motion moves through all microstates with equal probability, if most microstates correspond to a particular macrostate, that's the state that the system will move towards.This is basically the second law of thermodynamics.

Perhaps the simplest example of this that lets us work out the math of this is a set of objects that take two states. The microstate is the specification of the state of each object; the macrostate is the specification of how many of each state is present. A simple physical example of this is the flipping of a set of fair coins that can come up either heads (H) or tails (T).

Part 1: Coin tosses

Consider a set of N coins. If we toss each coin, each has two ways of coming down, H or T. Since the first coin can come down 2 ways, and the second coin can come down 2 ways, etc., the number of different ways (microstates) that the N coins can come down is 2 x 2 x ... (N times) = 2^N. While this is interesting, this is not the number we want. Rather, we want to know if we choose a particular macrostate (a given number of heads and tail) how many microstates correspond to that macrostate. That is, how many different ways could you get a string of coin flips that came up with that particular number of heads and tails?

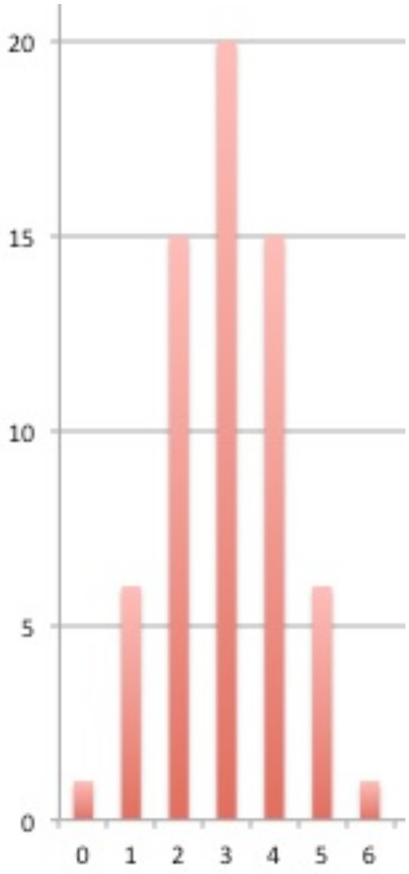
A. For 4 coins, count explicitly how many different ways there are to get each of the following macrostates:

- 4H, 0T
- 3H, 1T
- 2H, 2T
- 1H, 3T
- 0H, 4T.

B. Now suppose that you had N coins. Create an mathematical expression that would allow you to calculate how many different ways you could create a string of flips that would give M heads and (N-M) tails. Consider a set of N coins that have M heads and N-M tails showing. How many different ways could you choose a sequence of the coins? (*Hint:* You could choose the first one in N different ways. You could then choose one of the remaining N-1 in N-1 different ways; etc.) Since we don't care what order we get the heads or tails in, you have to divided by the number of ways of permuting the heads and the tails. This result is called ${}_NC_M$, the number of ways of choosing M objects out of a set of N without respect to order. (What you are to do for this part of the problem is justify the expression for the number of combinations in terms of the relevant factorials by describing the choosing and arranging process.)

C. Use a spreadsheet to draw bar graphs of the number of microstates of coin flipping to get M heads out of N flips, ${}_{N}C_{M}$, as a function of M for N = 10, 20, and 30. (You probably want to use the FACT(N) function which gives the value of N factorial (N!). An example of such a bar graph for N=6 is shown at the right. We see that 3H, 3T is the most likely result and 6H or 6T only have one way of getting them.

Once you have these bar graphs, fill out the following table that shows: the fraction of the total that correspond to the 50-50 macrostate; the half-width of the peak (about how far down you have to go on each side of the middle for the number to fall to half -- just eyeball it); and the ratio of the half width compared to N. The values for 6 are given in the table below.



N	**Total number of different ways the result can come out**	**Fraction of microstates that correspond to 50-50 (the most common macrostate)**	**Half width (eyeball it)**	**Half width / N**
6	$2^6 = 64$	20/64 = 0.31	~3	3/6 = 0.5
10				
20				
30				

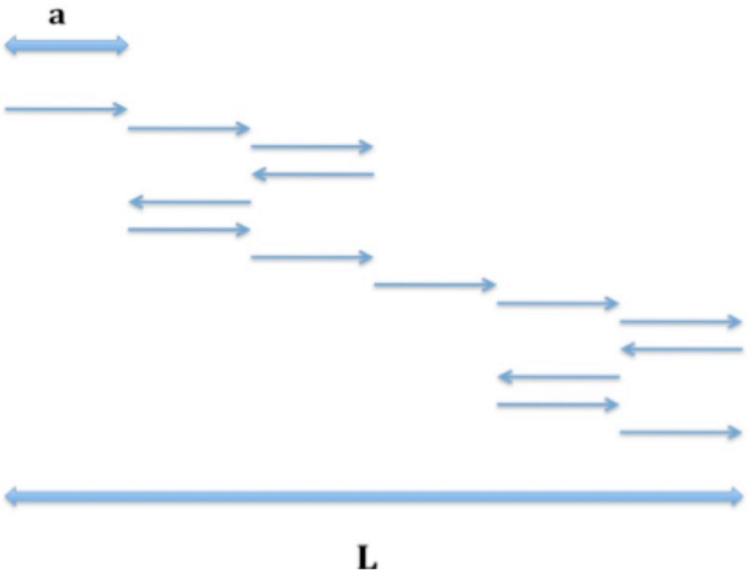
Does the peak get wider or narrower as the number of total flips goes up?

Part 2: Polymer folding

Consider a polymer like DNA. One very simple model of such a polymer is to assume that the polymer forms a one-dimensional chain consisting of $N >> 1$ links, each having a particular length a. Each of the links in the chain may be freely oriented to the right or left, with no energy difference between these two orientations. The likelihood that each link in the chain orients to the left or the right is precisely 50/50, just like a coin toss.

Suppose that n_R is the number of elements oriented to the right and n_L is the number of elements oriented to the left, such that $N = n_L + n_R$.

A. Refer to the figure at the right, in which one possible conformation of polymer links is illustrated (but where the individual links have been distributed vertically for clarity). For the example drawn, what are the values of N, n_R, and n_L? For the example drawn, what is the value of L in terms of the link length a?



B. Write down a general expression for the end-to-end extension of such a chain, L, in terms of the parameters n_R, n_L, and a. Of course, for the particular configuration drawn, your general expression must reduce to $L = 6a$.

C. Write down an expression for the number of arrangements W as a function of the total number of links N and the number of links pointing left or right, n_L and n_R. Explain your reasoning. (*Hint:* Refer back to your analysis in part 1.)

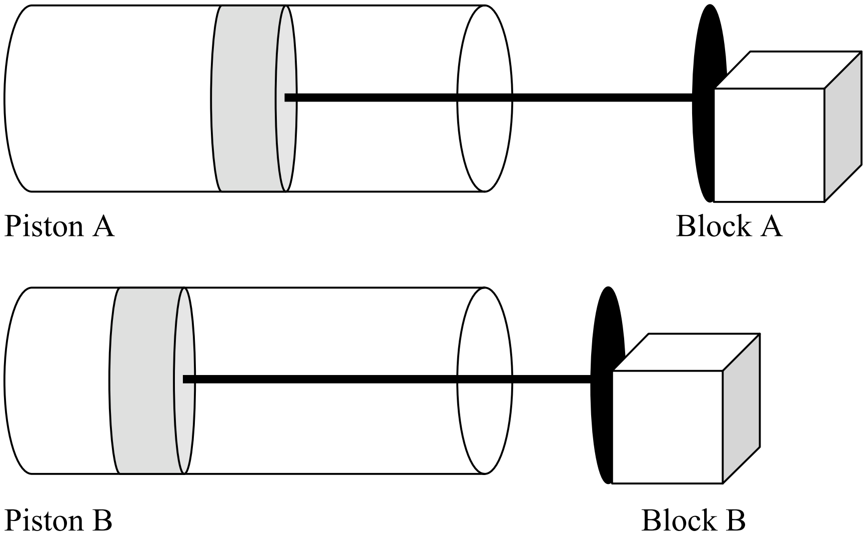
D. What would the state of minimum and maximum entropy of this polymer look like?

E. Can you use your results from parts A-D of this problem (and the second law of thermodynamics) to predict what you think the natural state of such a polymer would most likely look like?

Recitation Task:
What is "Free" about Free Energy?

Part 1.

Consider two pistons each containing an *equal amount of monatomic ideal gas* and each in *thermal equilibrium with the same environment*. The gas in Piston A is compressed to a volume $V/2$, and the gas in Piston B is compressed to a volume $V/4$. The pistons are *held in place until the moment of release*, at which point each is allowed to push on a block positioned next to it as shown:



1. After the pistons are released, describe the motion of Block A and Block B. Which moves a greater distance?

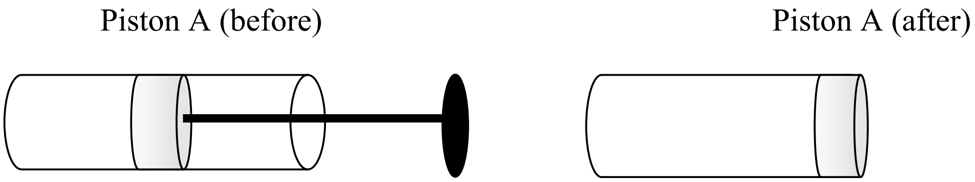
2. If the Figure above represents the "before" state, draw a similar picture showing the state "after" the pistons have been released and the blocks have finished traveling.

3. Before the pistons are released, how does the energy of the gas in Piston A compare to the energy of the gas in Piston B? How do you know? (*Hint: recall that* $U = 3/2kT$ *for a monatomic ideal gas*) What type of energy is it?

4. Compare your answers to Questions 1 and 3 above. Are they consistent or not? Discuss with your group!

Part 2.

Now let's think about what happens to the entropy and free energy of the gas during the expansion process described in Part 1. For clarity, let's focus in on just the gas in the piston and ignore the block for now. Assume a lightweight, frictionless piston, so that the gas does no work on the piston while it expands (this scenario may remind you of the clicker questions from class in which a partition was removed between the two sides of a container of gas). The piston in both the before and after states is in thermal equilibrium with the same environment.



1. How does the **energy *U*** of the gas after the expansion compare to the energy of the gas before the piston is released? How do you know?

2. How does the **entropy *S*** of the gas after the expansion compare to the entropy of the gas before the piston is released? Explain your answer.

3. How does the **free energy *G*** of the gas after the expansion compare to the free energy of the gas before the piston is released? How do you know? (Hint: recall that $H = U + PV$ and $G = H - TS$)

Part 3.

Now let's put together the pieces of the story.

1. In Question 3 of Part 1, you related the energy of the gas in Piston A to the energy of the gas in Piston B before the release of the piston. Now let's relate the <u>*free*</u> energy of the gas in Piston A to the <u>*free*</u> energy of the gas in Piston B before the release of the piston. To do so:

a) Compare the entropy change of the gas in Piston A during the expansion to the entropy change of the gas in Piston B during the expansion.

b) Use this to compare the free energy change of the gas in Piston A to the free energy change of the gas in Piston B during the expansion.

c) How does the initial free energy of Piston A compare to the initial free energy of Piston B?

2. Considering the effects that the pistons had on their respective blocks, what is misleading about the commonly heard statement that “energy is the capacity of a system to perform mechanical work”?

4. The total energy of a system is its free energy plus “something else.” What might be a good term to use for this “something else”? How does a change in entropy affect a system’s free energy?

5. What role does *pressure* or *pressure gradient* play in the scenario described in Part 1? For this example, could you come up with an operational definition of free energy in terms of pressure gradients?

Recitation Task: Salt Water

*In recitation you had a qualitative discussion about the energetic and entropic effects associated with dissolving salt in water. In this problem you'll have the opportunity to be a bit more quantitative, and to see the essential role that **entropy** plays in the ability of electrolytic ions to remain soluble in an aqueous cellular environment.*

Why electrolytes?

An electrolyte fluid contains ions that are essential to keeping the physiological engine running smoothly. They help to regulate the hydration of the body, the pH of blood, and an organism's nerve and muscle functioning. Every higher life form that we know of requires a subtle balance of electrolyte ions (most notably Na+, K+, Ca2+, Mg2+, and Cl-) between the intracellular and extracellular environment in order to maintain proper functioning. Sodium is the main electrolyte found in extracellular fluid and is primarily responsible for blood pressure control and fluid balance. For that reason and others, it is essential to our survival that NaCl be soluble in physiological environments. Let's see why it is!

Why *does* salt dissolve in water?

Dissolving a solute like NaCl in a solvent like H_20 can be thought of as a three step process: (1) the solute must be broken up into its component ions, (2) the solvent molecules must be separated to make room for the solute, and (3) solute-solvent interactions must form. Each step in that process is associated with an enthalpy change ΔH:

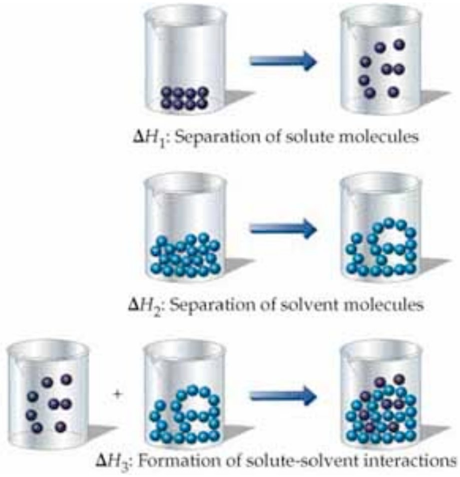


Figure 1. The three-step process by which a solute dissolves in a solvent. The enthalpy change associated with Step 1 is called the **lattice enthalpy**, since it is the enthalpy associated with breaking a solute lattice. The sum of the enthalpies

associated with Steps 2 and 3 is called the **hydration enthalpy**, since it's the enthalpy associated with surrounding the solute ions by water molecules.

A molecular depiction of Na^+ and Cl^- ions dissolving in water looks something like this:

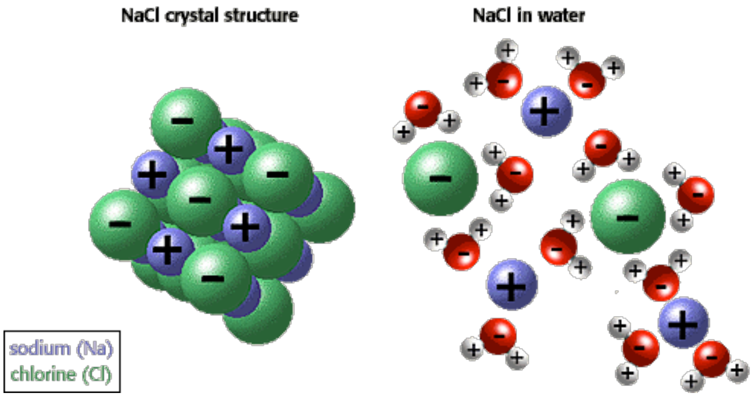


Figure 2. The NaCl ionic lattice is disrupted and the individual ions are surrounded by water molecules.

The lattice enthalpies for some ionic compounds and the hydration enthalpies, as found experimentally, are given in the following Table.

Ionic Compound	Lattice Enthalpy (kJ/mol)		Cation	Ion Radius (pm)	Hydration Enthalpy (kJ/mol)
LiF	1030		Li+	90	-515
NaF	910		Na+	116	-405
NaCl	788		K+	152	-321
KCl	701		Rb+	166	-296
KBr	671		Cs+	181	-268
CsCl	657				
MgCl2	2326		Anion		
CaO	3414		Cl-	167	-364

1. Use the pictures in Figure 2 to explain why the lattice enthalpies are positive and the hydration enthalpies are negative.

2. Use the pictures in Figure 2 to explain the correlation between ion radius and hydration enthalpy for cations. Why might the anion Cl^- not fit with that trend?

3. What is the overall enthalpy change for dissolving table salt (NaCl) in water? What does the sign of the overall enthalpy change indicate, if anything, about the solubility of salt in water?

4. As you know, table salt *is* soluble in water at room temperature! What does this tell you about the sign of the overall entropy change ΔS_{tot} upon dissolving salt in water? How do you know?

5. You found the sign of the overall entropy change ΔS_{tot} for dissolving salt in water in Question 4. If we let $\Delta S_{\mathrm{tot}} = \Delta S_{\mathrm{salt}} + \Delta S_{\mathrm{water,}}$ what are the signs of the individual ΔS_{salt} and $\Delta S_{\mathrm{water}}$ values? How do you know?

6. What effect would increasing the temperature have on the solubility of salt in water? How do you know?

7. Do the results you found in this problem agree with your qualitative discussion in recitation about the sign of ΔH and ΔS upon dissolving salt in water? If not, why not?

Recitation Task: Insane in the Membrane
Part 1: Oil and Water

First, imagine a box full of two types of non-interacting gases such as helium (He) and neon (Ne) in equal amounts.

1. Draw a picture of how you would imagine they would be distributed in a box.

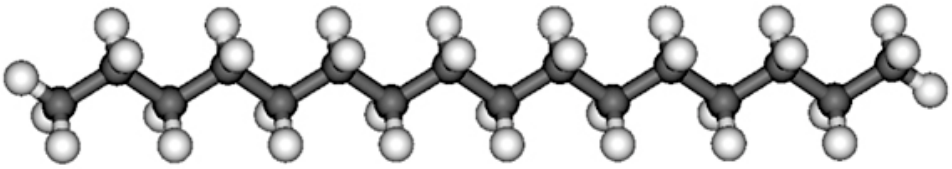
2. Based on what you know about entropy, can you justify why this would be the state that you observe?

In your study of biology, you've probably encountered "hydrophobic interactions": some nonpolar molecules, or nonpolar parts of molecules, seem to be repelled by water. This phenomena plays an important role in the structure of proteins, and next week we'll see how it relates to the formation of lipid bilayers: the membranes that form the boundary of all cells (as well as some organelles within cells). You've also encountered hydrophobic interactions in everyday life when you've observed that oil doesn't mix with water; they separate when you try to put them together.

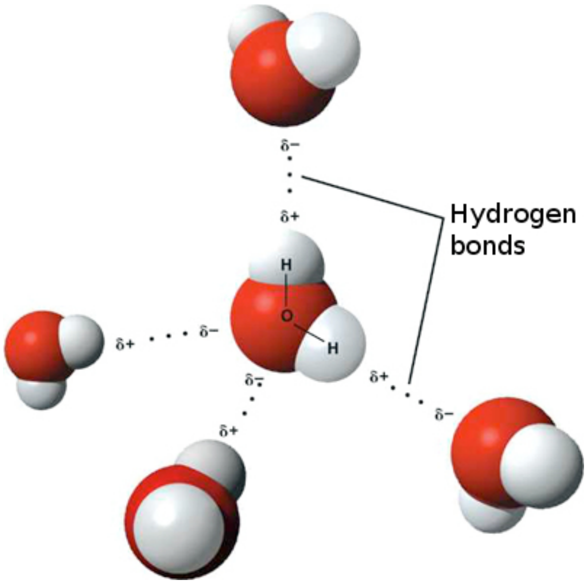
Today you'll use the Second Law of Thermodynamics to understand where this interaction comes from.

3. Draw (in a way that makes sense to you) what it would look like at the molecular level (a) for oil and water to mix, and (b) for oil and water to separate (don't worry about correctly representing the molecular structure of the oil, you can just use squares for oil molecules and triangles for water molecules.)

Oil molecules are basically long hydrocarbon chains. These are nonpolar molecules. The picture below shows an oil molecule with a carbon backbone (dark circles) and hydrogen atoms (white circles) coming out off of the backbone.



Water, in contrast, is a polar molecule: the electrons are closer to the oxygen atom than to the hydrogen atoms, and the molecule is bent so that both hydrogens are to one side, so the hydrogen end is positive and the oxygen end is negative. This results in hydrogen bonding: the reason that water is a liquid at room temperature (even though hydrogen and oxygen are gases). The picture below shows water molecules forming hydrogen bonds with one another where the large red circles represent oxygen, and the smaller white circles represent hydrogen.



4. Oil molecules can appear to get "stuck" inside surrounding water molecules (and, since an oil molecule is considerably larger than a water molecule, quite a few water molecules are required to surround a single oil molecule). Using what you know about hydrogen bonding between water molecules, draw a picture showing a hydrogen-bonded "cage" of water molecules within which an oil molecule is apparently stuck.

5. What effect does the formation of these hydrogen-bonded cages around oil molecules have on the entropy of the whole oil/water system (as compared to the situation where nothing "sticks" to anything and everything moves around freely)? Why?

6. Compare what will happen to the entropy of the whole system in the following two scenarios: A) if the oil molecules are all clumped together and the clump is surrounded by water and B) if the oil molecules are spread out evenly throughout the water, each individual oil molecule surrounded by water?

7. Explain from the perspective of entropy and the Second Law why it is that oil and water are likely to separate.

8. Your answer to question #2 may have suggested that oil and water would mix due to entropy, but in #7 you found that maximizing entropy would indicate that oil and water separate. How can you reconcile these two different answers?

Note: We have neglected to explicitly consider the energetic interactions between oil and water. Stay tuned... we'll add those interactions in next week!

Recitation Task: Insane in the Membrane
Part 2: Lipid Bilayers

How did life originate?

Many of the early models of life's origins proposed by biologists included as a crucial step the formation of **proto-cellular compartments** that could serve as distinct / discrete environments in which chemical reactions could take place. However, the exact structure and mechanism of their formation remained unknown.

In the 1960s laboratory experiments demonstrated that **phospholipids** could spontaneously assemble into bilayer membranes forming bacteria-sized containers (vesicles). Later experiments demonstrated that such vesicles could also form under simulated early-Earth conditions. Such experiments paved the way for a line of research investigating how these self-assembling membranes could have functioned in the evolution of living cells.

But how exactly does spontaneous membrane formation work? What are the mechanisms that drive this process? It turns out that an **understanding of the combined effects of energy and entropy** can help us make sense of this phenomenon.

1. Last week you explored the *entropic* contribution to hydrophobic interactions (the entropic reason for why oil and water don't mix). With your group, write out an explanation for why oil and water don't mix that relies only on the *entropic* arguments you made last week. (This explanation is incomplete because it does not yet take *energy* into account.)

Phospholipids have a phosphate ion at one end, and the rest is a hydrocarbon chain (like oil). The hydrocarbon end is the "hydrophobic" ("afraid of water") end. The phosphate end is the "hydrophilic" ("water-loving") end.

2. Gibbs free energy ($\Delta G = \Delta H - T\Delta S$) is a way of quantifying the (sometimes competing, sometimes additive) effects of *both* <u>energy</u> *and* <u>entropy</u>. You can think about what happens when you put hydrophilic molecules into water, and what happens when you put hydrophobic molecules into water, as resulting from both an energetic contribution (in this case, electrical potential energy) and an entropic contribution. Answer the following questions for the process of <u>oil separating from water</u> that we looked at last week:

- What is the sign of $T\Delta S$ for the system during the separation? How do you know?

- What interactions contribute to ΔH for the system during the separation? What is the sign of ΔH for each interaction that contributes to the overall ΔH? (Remember that ΔH is due to electrostatic interactions, so you are being asked to identify the various electrostatic interactions that one must consider.)

- It turns out that the quantitative value for ΔH upon separation of oil and water under standard conditions is quite close to zero! Why might that be plausible?

- What is the sign of ΔG for the separation of oil and water under standard conditions? What does this tell us about the separation?

3. As you know, not all substances behave like oil: some substances are soluble in water and dissolve quite easily. Think about ions (such as phosphate, or sodium chloride, or whatever) that tend to be soluble in water, whereas oil is not. Answer the following questions for the process of sodium chloride dissolving in water (the system is the water plus the salt):

- What is the sign of $T\Delta S$ for the system during the dissolving process? How do you know?

- What is the sign of ΔG? How do you know?

- What is the sign of ΔH for the system during the dissolving process? How do you know?

- How does this salt water system differ from the oil/water system?

4. Using Gibbs free energy, explain what makes some molecules (or parts of molecules) hydrophobic and others hydrophilic.

5. Explain why changing the temperature of the system can determine whether a substance dissolves in water or does not.

6. Putting all this together, explain how phospholipids can spontaneously self-assemble into a lipid bilayer. Why this particular shape? (Why not a monolayer, or a trilayer?) Note that the individual phospholipid molecules are still free to move around within the bilayer, like a two-dimensional liquid; they're not bound together like a solid.

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