Received: 12 August 2024 | Accepted: 5 March 2025

DOI: 10.1002/bmb.21894

ARTICLE

Biochemistry and Molecular Biology Education WILEY

# Visual representations of energy and chemical bonding in biology and chemistry textbooks: A case study of ATP hydrolysis

**Mingyu Yang**[1] | **Bryan C. Armpriest**[2,3] | **L. Kate Wright**[3] | **Dina L. Newman**[3]

[1]Department of Cell and Developmental Biology, University of California San Diego, La Jolla, California, USA

[2]Department of Biology, State University of New York at Geneseo, Geneseo, New York, USA

[3]Thomas H. Gosnell School of Life Sciences, Rochester Institute of Technology, Rochester, New York, USA

**Correspondence**
Mingyu Yang, Department of Cell and Developmental Biology, University of California San Diego, La Jolla CA 92093, USA.
Email: ymy@ucsd.edu

**Funding information**
National Science Foundation, Grant/Award Number: 2149957

**Abstract**

Energy is a crosscutting concept in science, but college students often perceive a mismatch between how their biology and chemistry courses discuss the topic. The challenge of reconciling these disciplinary differences can promote faulty reasoning—for example, biology students often develop the incorrect idea that breaking bonds is exothermic and releases energy. We hypothesize that one source of this perceived mismatch is that biology and chemistry textbooks use different visual representations of bond breaking and formation. We analyzed figures of ATP hydrolysis from 12 college-level introductory biology textbooks and coded each figure for its representation of energy, bond formation, and bond breaking. For comparison, we analyzed figures from six college-level introductory chemistry textbooks. We found that the majority (70%) of biology textbook figures presented ATP hydrolysis in the form "one reactant → multiple products" and "more bonds in reactants → fewer bonds in products". In contrast, chemistry textbook figures of the form "one reactant → multiple products" and "more bonds → fewer bonds" were predominantly endothermic reactions, which directly contradicts the exothermic nature of ATP hydrolysis. We hypothesize that these visual inconsistencies may be a contributing factor to student struggles in constructing a coherent mental model of energy and bonding.

**KEYWORDS**

ATP, biochemistry, visual representations, introductory biology, introductory chemistry

## 1 | INTRODUCTION

### 1.1 | Chemical bonding and energy

Energy is a key crosscutting concept in the physical and life sciences.[1–3] Although the physical laws governing energy are universal, different academic disciplines adopt different conventions when discussing and teaching the topic of energy,[4–6] which can lead to students constructing a fragmented understanding of the concept. Prior studies show that college students conceptualize energy differently depending on course context and struggle to transfer their knowledge about energy across disciplines.[6,7] This is a problem because developing a complete understanding of energy is a necessary prerequisite for understanding many biological and physical phenomena.

One of the most commonly held misconceptions about energy is that breaking chemical bonds releases energy, when in fact the opposite is true.[8–10] This misconception is especially prevalent in biology students' reasoning about adenosine triphosphate (ATP), a molecule that plays a key role in bioenergetics and cellular metabolism.[11] When a molecule of ATP is hydrolyzed, ATP reacts with water to produce adenosine diphosphate (ADP) and inorganic phosphate ($P_i$). This reaction involves breaking a covalent bond in the ATP molecule to remove the terminal phosphate group, a process that requires an input of energy (consistent with any process that involves breaking a chemical bond). This energy input is offset by the energy released in forming new, more stable bonds in the products (ADP and $P_i$). Since more energy is released than consumed in this reaction, ATP hydrolysis is overall an energy-releasing, exothermic reaction.[12]

When biology students are asked to explain why ATP hydrolysis releases energy, their answers often reveal, erroneous mental models of energy being 'liberated' upon bond breaking.[7,10,11] In one qualitative study, a student stated that "*ATP, when the bond's broken, energy is released ... when one of the phosphates is broken off, it releases energy. That's, I think, what's getting me. Because when the bond's broken, it should absorb energy. So, I'm getting very confused.*".[7] Other biology students perceive a similar dissonance between chemistry and biology courses, with one student stating "*I just learned something* (bonding) *in two opposite ways... I actually still don't really understand it, to be honest. I don't really know which one's right*".[7] This confusion is likely exacerbated by the common explanatory shorthand of describing ATP as containing "high-energy bonds".[13–17] This phraseology has historically been widely used in biology textbooks[16] and may contribute to the problematic mental model of ATP's bonds as 'bursting' to break, akin to an unstable dam that releases a flood of energy upon collapse. Misconceptions about exothermic bond-breaking are also likely influenced by students' lay-theories about energy, formed outside of the biology classroom. For example, in one survey of 600 biochemistry and physiology students, 80% selected bond breaking as the main cause of energy release during the combustion of fuels, which may reflect the ubiquity of lay-explanations involving "breaking down chemicals" for energy.[10]

Furthermore, the emphasis placed on ATP *hydrolysis* in biology textbooks may itself be misleading because ATP is rarely actually hydrolyzed in biological systems. ATP hydrolysis is typically characterized as the one-step conversion of ATP to ADP and inorganic phosphate ($P_i$), accompanied by energy *release*.[13] In reality, ATP-coupled processes in biology actually involve energy *transfer*, typically via a reactive phosphorylated intermediate.[18] Nonetheless, ATP hydrolysis continues to be a standard part of introductory biology curricula, evident in the ubiquity of this topic across all introductory biology textbooks. Furthermore, ATP hydrolysis has been specifically singled out as a topic that contributes to the misconception of exothermic bond breaking,[8–10] making it a topic that warrants further investigation. Therefore, we constrain the scope of the present study to representations of ATP hydrolysis since this topic most directly elucidates potential discrepancies between chemists' and biologists' ways of thinking.

## 1.2 | Resources framework

A helpful theoretical framework for characterizing student conceptions of energy is the *resources framework*, initially developed by physics education researchers.[19–21] The resources framework posits that learners possess a set of cognitive resources, each of which represents a separate piece of their conceptual knowledge. Students activate different resources in different contexts, and accessing incomplete subsets of these resources can lead to erroneous conclusions. For example, biology students may possess the conceptual resources that 'ATP hydrolysis releases energy' and that 'ATP hydrolysis involves breaking a phosphodiester bond'. Even though these resources represent correct statements in their own right, if activated in isolation they can lead to the erroneous conclusion that ATP hydrolysis releases energy because breaking the phosphodiester bond releases energy. Indeed, biology students may also possess the conceptual resource that 'breaking chemical bonds requires energy', likely acquired from prior or current chemistry coursework. But if this critical resource is left inactivated, this important fact may be ignored, thus leading students to the erroneous conclusion that bond breaking releases energy. In this way, the resources framework provides a more fine-grained lens of explaining errors in students' reasoning; instead of viewing errors as fixed, monolithic beliefs, we can instead view them as stemming from incomplete activation of disparate conceptual resources. This framework explains how students can arrive at erroneous conclusions even when the underlying pieces of knowledge are all individually correct. Furthermore, the resources framework accounts for the tension students experience when they detect having "*learned something in two opposite ways*", for instance when they devise an explanation (e.g., "breaking the bond in ATP releases energy") that directly contradicts with an existing conceptual resource (e.g., "breaking chemical bonds requires energy").

### 1.3 | Characterizing disciplinary differences

An important first step in understanding *why* students perceive the same concept (ATP hydrolysis) differently in chemistry versus biology is to characterize *what* instructional resources students encounter in biology and chemistry classrooms. We propose that one source of disciplinary mismatch is that each field uses distinct visual representations of chemical bonding, which may expose students to mutually contradictory models of bond breaking and formation. Visual representations are essential for biology and chemistry because they "help to make the unseen seen and the complex simple".[22] Often, there is no one "correct" way to represent something in the molecular world. For example, a single protein can be represented using a ball-and-stick model, space-filling model, or a ribbon backbone. This example demonstrates both the utility and limitation of visual representations; representations can highlight different important features of phenomena, but they are necessarily incomplete and must leave out crucial details. When learning a concept for the first time, a student's task is to connect these visual representations into a unified whole. However, prior studies show that students struggle to connect multiple visual representations of the same phenomena, focusing on surface-level differences despite the underlying concept being the same.[23,24] Therefore, if biologists and chemists use different visual representations of ATP and bonding, those surface visual differences may obscure for students how the underlying laws of energy are in fact the same across both disciplines.

There is a large body of literature on visual representations in biology and chemistry instructional resources, typically focusing on science textbooks. Several groups have tabulated the number, types, and levels of representations in chemistry textbooks,[25–28] and others have focused on biology textbooks.[29,30] To our knowledge, all such studies have focused on *either* biology or chemistry, and none make a direct comparison between the two. Given that college students struggle with connecting different visual representations, and they especially struggle to reconcile chemistry and biology concepts, we sought to precisely characterize how visual representations of bonding differ across introductory biology and chemistry textbooks. Specifically, we explored the following research questions.

1. What visual representations are used in biology textbooks to depict energy and ATP hydrolysis?
2. How do representations of energy and ATP hydrolysis in biology textbooks compare to representations of bond breaking, bond formation, and energy in chemistry textbooks?

Studying textbook figures is pertinent because many instructors often use these as the basis for their lecture slides; even if students themselves may not read textbooks, they will often encounter the figures from those textbooks in their course materials. Therefore, if biology textbooks contain features that contradict what students learn in chemistry, this can lead to confusion. Furthermore, some biology instructors may feel unconfident teaching about ATP[13] and often use textbook materials to refresh their own subject knowledge before teaching. By pinpointing *which* visual representations are used across biology and chemistry instructional resources, we hope to motivate future work on *whether* and *how* those differences may contribute to students' alternative conceptions. The present study represents a first step toward attaining this goal, by unpacking how biology and chemistry textbooks differ in their visual presentation of these crosscutting concepts.

## 2 | METHODS

### 2.1 | Selecting figures for analysis

First, we identified a set of 10 college-level introductory biology textbooks (Supplementary Table 1), all of which were published within the past 8 years. This set of textbooks was chosen using Simon et al.[31] textbook list as a starting point. In total, we identified 30 figures depicting ATP hydrolysis, ranging from one to five figures per textbook. To maximize objectivity in the figure selection process, one coder (M.Y.) identified the first figure in which ATP hydrolysis was represented in each textbook. Then, all subsequent figures depicting ATP hydrolysis from that same chapter were compiled for analysis. Since all textbooks had essentially the same content order, every figure ultimately originated from the 'introduction to metabolism' chapter. Any figures in later chapters, even if they contained ATP, were excluded from analysis. This strict inclusion criterion was chosen so that all figures were specifically *about* ATP hydrolysis, as opposed to illustrations that focused on other biological phenomena in which ATP happens to play a role. For example, every textbook also contained figures depicting membrane transport and muscle physiology in later chapters, which included ATP, even though the focus of each illustration was not ATP itself. Such figures were excluded from the scope of analysis. Our goal was for the figures to capture what students are exposed to during their first exposure to ATP hydrolysis as an energy-releasing reaction.

Furthermore, figures from the subsequent respiration and photosynthesis chapters, which contained 'ATP' written in almost every figure and metabolic pathway, were also excluded from the current scope. An additional biological reason to justify this exclusion is because ATP-mediated reaction coupling is more complex than just a simple hydrolysis reaction. Many of these ATP-dependent processes included in the respiration and photosynthesis chapters involve phosphorylation to form a reactive intermediate, for example in glutamine synthesis[18]; arguably, 'hydrolysis' alone would be an overly reductionist label for the role that ATP plays in these reactions. We chose to limit our scope to ATP hydrolysis because (a) there are widely documented misconceptions about this topic in particular, (b) for better or worse, the topic is widely taught in biology classrooms, indicated by its ubiquity in biology textbooks, and (c) our goal was to take a deep dive into the visual representations used for one specific concept, as opposed to provide a holistic view of ATP-coupled reactions in general. In all biology textbooks studied, figures of ATP hydrolysis directly preceded figures of more biologically meaningful, ATP-coupled reactions involving phosphorylated intermediates. Future work will investigate how these more complex (and more biologically relevant) ATP-coupled reactions are presented. We argue that the focus of this study is not actually about ATP hydrolysis itself, but rather how this reaction is a case study for how biology textbooks visually represent energy and chemical bonding.

Then, we analyzed a convenience sample of six college-level introductory chemistry textbooks (Supplementary Table 2), all of which were published within the past 8 years. Since ATP hydrolysis is not a core topic of general chemistry curricula, as expected, most of these textbooks contained at most one figure representing ATP, if at all. We instead focused on the visual representation of chemical bonding, bond formation, and bond breaking *in general*. To do this, we identified a total of 33 figures across the chemistry textbooks, ranging from six to eleven figures per text. To determine which figures to select, we searched the textbooks for the words "exothermic reaction" and "breaking bonds" and found the first chapter in which both phrases co-occurred. As a result, these figures all originated from the chapters in which chemical bonding and energy are first introduced, much in the same way that the biology figures originated from the chapter in which ATP hydrolysis was first introduced.

## 2.2 | Developing a codebook

One coder (M.Y.) selected one biology and one chemistry textbook and used an inductive approach[32] to list as many visual features as possible in each figure selected. This list of features was the preliminary codebook, which was subsequently revised through discussion with other researchers (D.L.N. and L.K.W.). Where possible, we tried to make each code an objective, visual property that did not require any biology or chemistry knowledge to detect (e.g., 'includes water', 'features a lightning bolt motif'). This was in an effort to increase inter-rater reliability *and* to allow the codes to transcend specific disciplinary content, thereby allowing the same coding scheme to be applicable to both biology *and* chemistry figures. Based on this approach, we generated the codebook shown in Table 1.

**TABLE 1** Description of codebook for analyzing biology and chemistry textbook figures.

| Code | Description |
|---|---|
| Level of structural representation | Full chemical structure, partial structure/cartoon, or whole with no parts (e.g., ATP represented as a monolithic circle with the text 'ATP' in it) |
| Inclusion of energy | Is 'energy' listed in words somewhere in the figure, together with either the reactants or the products? |
| Inclusion of water | (*Specific to biology textbook figures*) Is 'water' either listed in words or illustrated somewhere in the figure? |
| Use of lightning bolt/halo motif | Is a lightning bolt design found somewhere in the figure (e.g., a reactant and/or product that is encased in a yellow saw-toothed shape?). |
| Number of bonds in reactants versus products | How many bonds are illustrated in the reactants versus in the products? For partial structures/cartoons, number of points of contact shown within the reactant versus product molecules. |
| Number of distinct reactants versus products | How many distinct reactants versus products are there? (e.g., the reaction $A + B \rightarrow C$ would be coded as two distinct reactants and one distinct product.) |
| Other visual aids | What other visual aids are present to support reasoning? We coded for whether the figure singled out one bond as being a 'high-energy bond', whether the figure used a reaction coordinate diagram or illustrated an energy cycle, and whether the figure fully enumerated the bonds broken and formed in the reactants and products. |

### 2.3 | Coding and determining inter-rater reliability

Two coders (M.Y. and B.C.A.) independently coded the figures from the same two biology and chemistry textbooks, using the codebook categories outlined in Table 1. Then, the coders met to refine the coding criteria and disambiguate edge cases, and they each independently coded the remaining figures. We used the R package *psych* to calculate Cohen's kappa coefficient[33,34] for inter-rater reliability, which was 0.84 and 0.88 for the biology and chemistry figures, respectively, indicating strong agreement. The coders then met to reach resolution on disagreements and finish coding all figures to full consensus. The data shown in the rest of this paper represent the consensus code between M.Y. and B.C.A.

## 3 | RESULTS

### 3.1 | Visual representations of ATP in college biology textbooks

We coded each figure of ATP hydrolysis based on its level of structural representation, categorizing each figure into one of three groups: whole with no parts, partial structure/cartoon, and full chemical structure. Figure 1 shows recreations of a representative figure from each category. Note that the 'full chemical structure' category also contained visual representations featuring partial skeletal structures, such as where the nitrogenous base (adenine) and ribose were drawn in skeletal form. As long as the phosphate groups (the main active participant in the hydrolysis reaction) were drawn in full, a figure was binned into the 'full chemical structure' category. The majority (57%) of ATP hydrolysis figures represented ATP as a whole with no internal subparts, 47% of figures included a partial structure/cartoon, and 20% showed the full chemical structure. These percentages sum to above 100% because some figures used multiple levels of representation within the same illustration, for example showing ATP in cartoon form with a call-out box zooming into the phosphate groups' chemical structure.

We also coded each biology textbook figure for its representation of energy. The majority (74%) of biology figures included the text 'energy', although the location was inconsistent. Many (27%) of the figures positioned 'energy' adjacent to the hydrolysis products (i.e., at the same level as ADP and $P_i$), while others (47%) positioned 'energy' next to the reaction arrow (i.e., in between the reactants and products). Furthermore, the vast majority (86%) of figures included some variant of a lightning bolt/halo motif (Figure 2), although the location and meaning of this halo were heterogeneous both across and within texts. In 43% of figures, the halo motif encircled the ATP molecule; in 23% of the figures, the halo encircled the word 'energy'; and in 20% of figures, *both* the ATP molecule and energy were encircled by a halo. Furthermore, none of the figure captions included any text description that explicitly referred to the halo motif or what it meant.

### 3.2 | Comparison of visual representations across biology and chemistry textbooks

We found that both biology and chemistry textbook figures used visual aids to further reinforce the mechanism and directionality of energy transformations. Biology,

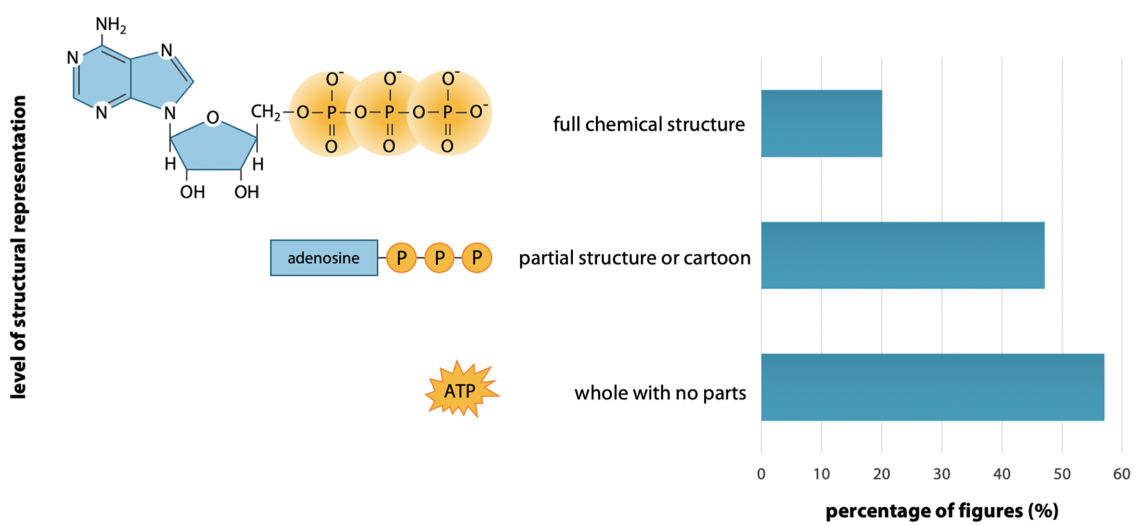


FIGURE 1 Level of structural representation of ATP hydrolysis in college biology textbook figures ($n = 30$).

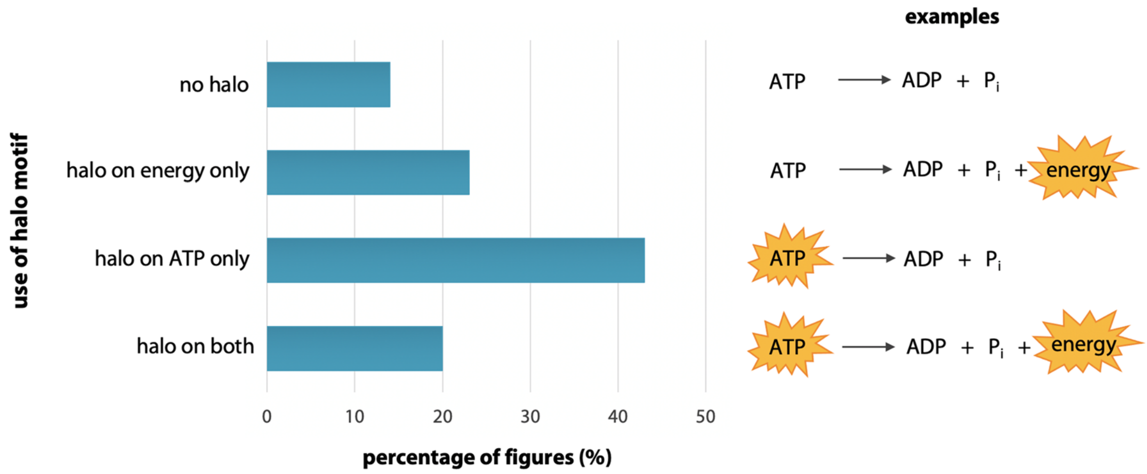


FIGURE 2 Use of halo motif to describe energy and/or ATP in college biology textbook figures ($n = 30$).

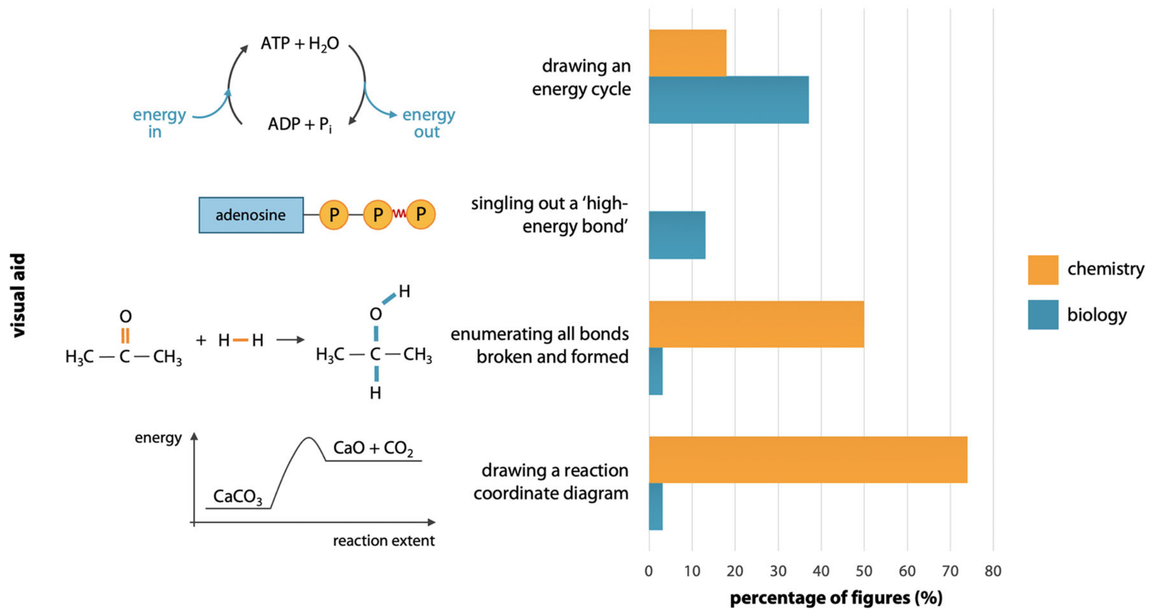


FIGURE 3 Prevalence of visual aids to support reasoning about energy in college biology textbook figures ($n = 30$) and college chemistry textbook figures ($n = 33$).

and to a lesser extent chemistry, textbook figures used energy cycles (like shown at the top of Figure 3) to illustrate the directionality of energy input and output and to emphasize the reversibility of chemical reactions. While 37% of biology textbook figures explicitly employed a cycle to represent ATP hydrolysis/synthesis, only 18% of chemistry figures illustrated an energy cycle.

Whereas energy cycles were common to both biology and chemistry textbooks, other visual aids were more siloed by discipline. Notably, 13% of biology figures singled out a "high-energy bond" in the reactant as the driving force for the reaction, whereas no chemistry figures highlighted a singular bond in this way. Although 13% is a relatively low percentage (perhaps indicating a general trend away from this type of representation), this finding still highlights that the metaphor of breaking a "high-energy bond" is essentially absent in chemistry.

Chemistry textbooks also used other visual aids that were largely absent in biology textbooks. The majority (74%) of chemistry figures used a reaction coordinate diagram to indicate how energy changed as a function of reaction extent, whereas only a single biology figure used this in the context of ATP. Furthermore, 50% of chemistry figures explicitly enumerated all the bonds broken and formed in the reactants versus the products, whereas this was done in only one biology figure. Every chemistry textbook enumerated the bonds in service of calculating the overall reaction energy, subtracting the energy

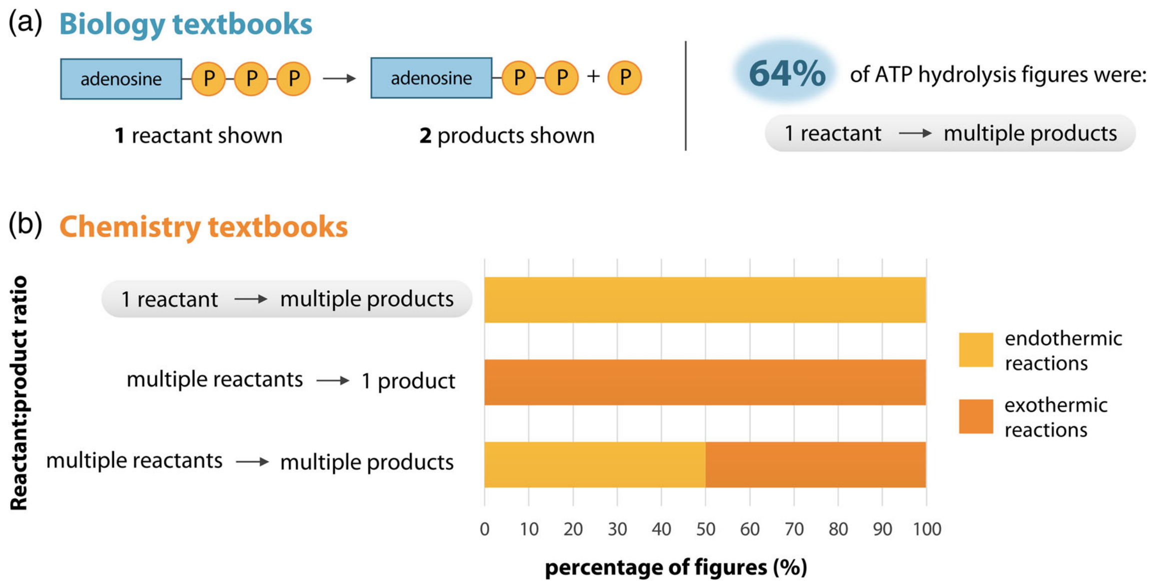


**FIGURE 4** Ratio of distinct reactants and products in biology and chemistry textbook figures. (a) Representative illustration of ATP hydrolysis in college biology textbooks, showing one reactant (ATP) becoming multiple products (ADP and $P_i$) (b) Stacked bar charts comparing the reactant: product ratio in endothermic versus exothermic reactions in chemistry textbook figures.

released through forming the products' bonds from the energy required to break the reactants' bonds. Such examples explicitly highlight the exothermic nature of bond formation and the endothermic nature of bond breakage, a key idea that is either implicit or absent in biology figures.

We next characterized the specific attributes of the reactants and products depicted in biology and chemistry textbook figures. We found that 64% of biology figures did not include water despite its critical role in ATP hydrolysis. In other words, 64% of all biology figures were of the form ATP → ADP + $P_i$ (Figure 4a). To generalize this result beyond ATP, we decided to classify these figures as being 'one reactant → multiple products', to capture the ratio of reactants versus products explicitly drawn. Next, we looked for all chemistry textbook figures of the form 'one reactant → multiple products' or 'multiple reactants → one product', and we determined whether each reaction was exothermic or endothermic.

Figure 4b shows that 100% of chemistry figures of the form 'one reactant → multiple products' depicted endothermic reactions. Almost all such reactions were instances of thermal decomposition, where a singular reactant breaks down into its constituent parts. One caveat is that in later chapters of chemistry textbooks (outside the scope of this analysis), there are occasionally reactions that appear to violate this trend. For example, ozone breakdown ($O_3 \rightarrow O_2 + O$) appears to be 'one reactant → multiple products' but is in fact exothermic. However, ozone breakdown is actually a multi-step reaction consisting of smaller elementary steps, and within these elementary steps, all reactions that are 'one reactant → multiple products' are endothermic. Our present analysis shows that students generally do not encounter such multi-step reactions that appear to violate the trend early on in their chemistry textbooks. In addition, we found that 100% of chemistry figures of the form 'multiple reactants → one product' depicted exothermic reactions. These results are notable because they are completely at odds with representations of ATP hydrolysis in biology textbooks. Even though 'one reactant → multiple products' is universally used for endothermic processes in chemistry, 67% of biology figures represent ATP in this way, when ATP hydrolysis is fact exothermic. Put differently, not a single chemistry textbook figure represents exothermic processes in the form 'one reactant → multiple products', even though this is the modal representation of ATP hydrolysis in biology textbooks.

Of course, ATP hydrolysis is not actually 'one reactant → multiple products' despite being illustrated as such. If water were included in these figures, the process would instead be 'multiple reactants → multiple products'. Unlike 'one reactant → multiple products' or 'multiple reactants → one product', which were universally associated endothermic and exothermic reactions respectively, 'multiple reactants → multiple products' can be *both* exothermic and endothermic. Indeed, in chemistry textbook figures there were numerous examples of both exothermic and endothermic reactions that were 'multiple reactants → multiple products', indicating that this configuration is amenable to both reaction types. This is chiefly because if a reaction exothermic, then its reverse

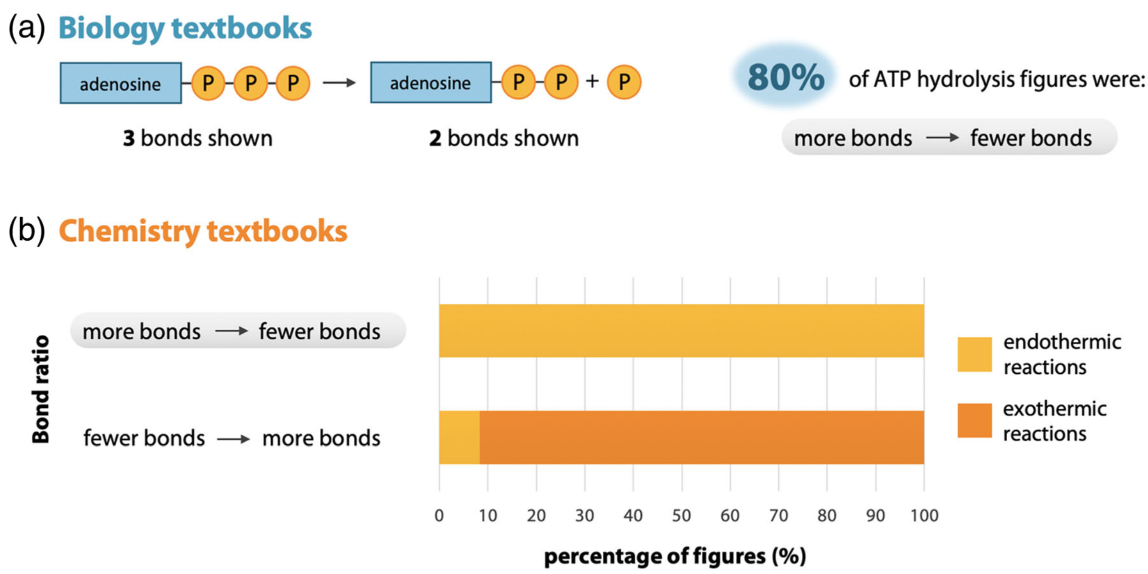


FIGURE 5 Ratio of bonds in reactants and products in biology and chemistry textbook figures. (a) Representative illustration of ATP hydrolysis in college biology textbooks, showing more bonds in the reactants (ATP) and fewer bonds in the products (ADP and $P_i$) (b) Stacked bar charts comparing bond ratios in endothermic versus exothermic reactions in chemistry textbook figures.

reaction is endothermic and vice versa (both forward and reverse reactants still being 'multiple reactants → multiple products').

In addition to the number of reactants and products shown, another salient feature of both biology and chemistry figures is the total number of *bonds* shown in the reactants and products. Consider the representative figure of ATP hydrolysis shown in Figure 5a. Even though this is a cartoon representation of ATP, there are still four distinct subparts shown (adenosine and three separate phosphates), joined by a total of 3 connecting lines/bonds. In contrast, only two connecting lines/bonds are depicted in the products. In fact, 80% of biology figures represent ATP in this way, of the form 'more bonds in the reactants → fewer bonds in the products'. Once again, we identified all chemistry figures of the form 'more bonds → fewer bonds' and 'fewer bonds → more bonds' and categorized each reaction as either exothermic or endothermic.

Figure 5b shows that 92% of chemistry figures that were 'more bonds → fewer bonds' are endothermic, and 8% are exothermic. The distinction is even sharper in the 'fewer bonds → more bonds' category, where 100% of these reactions were exothermic. Note again the contradiction between chemistry and biology textbook figures. Even though ATP hydrolysis is drawn as 'more bonds → fewer bonds' in biology textbooks, in chemistry textbooks the overwhelming majority of such reactions are endothermic.

Importantly, the result in Figure 5b is not as black-and-white as that of Figure 4b. Indeed, there *can* be exothermic reactions that are 'more bonds → fewer bonds', since the exothermicity of a reaction is about more than just counting the number of bonds. Bond *strength* is ultimately the deciding factor; if a reaction releases more energy in forming the products' bonds than it requires to break the reactants' bonds, then that reaction is exothermic. Therefore, it is entirely possible for an exothermic reaction to be of the form 'more bonds → fewer bonds', provided that the bonds broken in the reactants are relatively weak, and the bonds in the products are strong and release enough energy when formed to offset the initial energy input required. However, such examples are in the minority (7%), and the vast majority of exothermic reactions that chemistry students see are 'fewer bonds → more bonds'. This exemplifies yet another key representational contrast between biology and chemistry.

## 4 | DISCUSSION

### 4.1 | Representations of ATP hydrolysis in biology textbooks

Our work has elucidated a number of key differences between visual representations of ATP hydrolysis in biology textbooks and representations of exothermic reactions in chemistry textbooks. First, we found that biology and chemistry textbooks use distinct visual aids to support reasoning about the underlying energy transfers in a reaction. Biology figures highlighted "high-energy bonds" in the reactants, whereas no chemistry figures singled out one bond as the causal agent for a reaction. Furthermore, chemistry figures were more likely to use reaction coordinate diagrams and enumerate every bond broken and formed. An important caveat to these findings is that the context varied from figure to figure. Although all the biology textbook figures were designed specifically to explain ATP hydrolysis, the chemistry textbook figures were drawn from a broader chapter on reaction energetics in general. Since the context varied across figures, the change in context may preferentially motivate the use of certain visual aids over others. For example, a chemistry textbook figure drawn from the context of explaining ionic compound formation is more likely to use a reaction coordinate diagram to draw a Born-Haber cycle. Therefore, this context-dependence limits our ability to make direct one-to-one comparisons between biology and chemistry. Even so, we believe that making general comparisons is still valuable because all the chemistry textbook figures still focus on the common theme of *why* reactions are exothermic or endothermic from a bond breakage/formation point of view. Furthermore, we tried to draw chemistry textbook figures from the most generic chapter on chemical energetics most broadly, as opposed to one that had more specific contextual focus (e.g., ionic bonding). Therefore, key distinctions between chemistry and biology figures are still valuable to pinpoint – for example, it is notable that even with this broad chemistry context, the concept of a singular "high-energy bond" does not appear once in any chemistry textbook figure to justify reaction energetics. Unfortunately, this context variability is not a variable we could control, although we attempted to choose a chemistry textbook chapter that was most thematically related to bond breaking/formation and exothermicity/endothermicity, since these are the particular topics that students most struggle with in explaining ATP hydrolysis.[10]

Secondly, biology textbooks are inconsistent in their use of visual halos to represent energy and ATP. Prior studies already document that students are sometimes confused about the nature of ATP and energy. For example, in one study a student described ATP as "*a form of energy that can help a reaction take place*".[7] Other students provided similarly oversimplified descriptions of ATP as being equivalent to energy itself, as opposed to the more accurate characterization of ATP as a storage molecule. We speculate that one source of this confusion could be textbook figures in which ATP and energy are both highlighted with halos or symbolized with explosive bursts. Such figures could lead students to draw a false equivalence between the ATP molecule and energy, potentially implying that an ATP molecule is more similar in constitution to energy than to a molecule of ADP (which is drawn with no halo around it).

Furthermore, we found that the majority of biology textbook representations of ATP hydrolysis were of the forms "one reactant → multiple products" and "more bonds in the reactants → fewer bonds in the products", which was the opposite of how chemistry textbooks typically represented exothermic processes. One reason why biology textbooks may choose to omit water (thus creating the impression of "one reactant → multiple products") is because all biological reactions are assumed to take place in aqueous medium, therefore one could argue that including $H_2O$ in diagrams may appear redundant. While an undergraduate student may know that cells are 70% water, not explicitly showing a water molecule in the hydrolysis reaction may inadvertently remove important context for the learner. Therefore, future work will explore the extent to which the exclusion of water leads to meaningfully different interpretations of the image by students. We speculate that showing ATP hydrolysis as "more bonds → fewer bonds" could also be a contributing factor in students' thinking that ATP hydrolysis is purely a reaction of bond breakage and not bond formation. Importantly, future work is required to verify these hypotheses and determine which visual representations are meaningful to students' interpretations of the figures. Nonetheless, we believe our study represents an important first step in highlighting *what* those visual representations actually contain, providing a set of variables to manipulate in future work.

### 4.2 | A proposed framework for students' conceptual resources about ATP hydrolysis

Based on our results, we propose the model shown in Figure 6 of a student's cognitive resources regarding energy and bonding. In this model, conceptual resources that are typically acquired in biology instructional resources are color-coded in blue, and those from chemistry are color-coded in orange. Based on this model, we can hypothesize how partial inactivation of a student's resources can lead to erroneous conclusions about the mechanism of ATP hydrolysis. For example, if a student only activates resources 1 and 2 of Figure 6 ("ATP hydrolysis involves breaking a phosphodiester bond" + "ATP hydrolysis releases energy"), this can lead to the erroneous conclusion that "ATP hydrolysis releases energy because breaking unstable bonds releases energy". In drawing such a conclusion, a student is not accessing their chemistry resources that "forming bonds releases energy" and "breaking bonds requires energy".

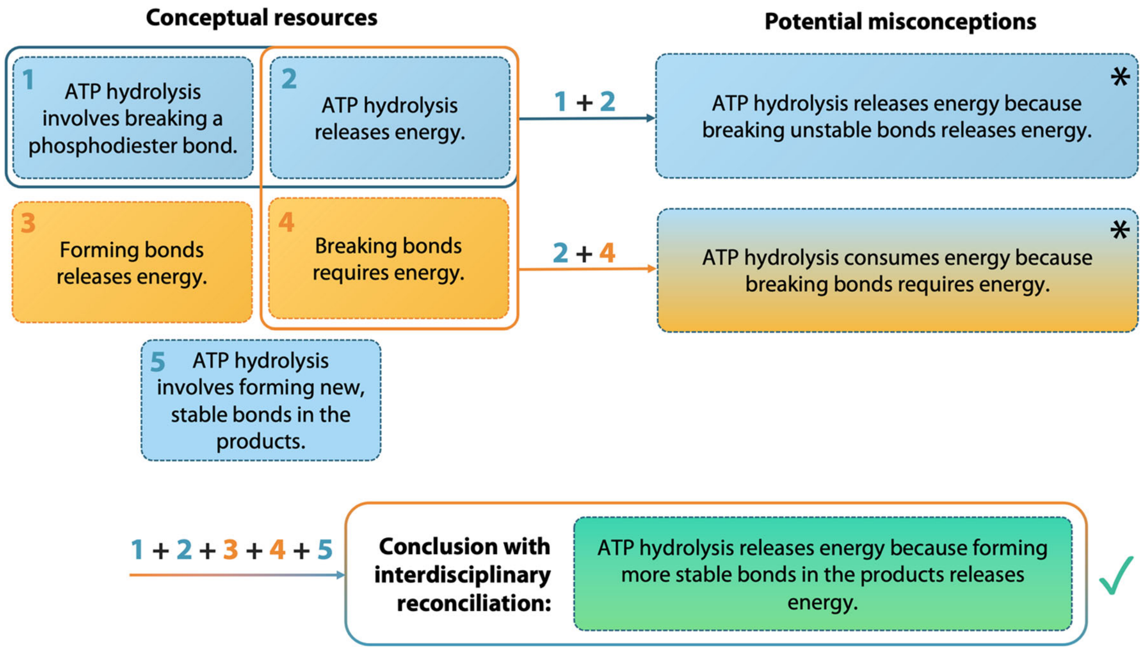


**FIGURE 6** Proposed model for a student's conceptual resources about energy and bonding, and how partial activation of these resources can lead to erroneous conclusions about ATP hydrolysis. Erroneous conclusions are indicated by an asterisk.

We hypothesize multiple reasons for students leaving their chemistry-specific conceptual resources inactivated. One possibility is that particular resources are missing to begin with. For example, students may lack the knowledge that "ATP hydrolysis involves forming new, stable bonds in the products", instead erroneously believing ATP hydrolysis to solely involve bond breakage. Therefore, if bond formation is not recognized as a key component of the reaction, there is no reason to activate the chemistry resource that "forming bonds releases energy". In addition, different visual representations may differentially prime students to activate particular subsets of resources. For example, if students are always seeing ATP hydrolysis in the form "more bonds in the reactants → fewer bonds in the products", this may further direct their attention toward bond breakage as being the essential component of ATP hydrolysis. Finally, students may be aware of their chemistry conceptual resources but actively suppressing them, because they anticipate that surfacing the resource can create cognitive dissonance. For example, one student in a previous study stated "*I feel like I can ration [sic] it out both ways, so then, I understand why someone would say either/or, but then I know for biology what [the instructor] wants us to say and then for chemistry what we have to say*".[7] Future work will explore the extent to which different visual representations contribute to students developing a unified or discordant set of conceptual resources.

## 4.3 | Limitations and future work

There are a number of limitations with this work. Although we sought to characterize differences between biology and chemistry visual representations, the present work does not survey students about how they *respond* to those differences. Future work will investigate how students interpret the different kinds of visual representations identified here, and whether different representations bias students toward activating different conceptual resources. Precisely characterizing the differences in what students see is a necessary prerequisite to understanding the effects of those differences on student reasoning.

Secondly, the scope of our textbook analysis focused only on the images and not the text. This focus on visual representations over text represents a broader trend in textbook analysis studies,[28] and future work will explore how ATP hydrolysis is described in the body of biology textbooks. In addition, we hope to explore how instructors are explaining ATP hydrolysis and bonding within their actual classroom context. Furthermore, textbooks are just one of many instructional resources used by students: future work could focus on characterizing online biology videos to broaden the scope of resources characterized.

In summary, this work presents a possible contributing factor to students' fragmented understanding of chemical bonding and energy. We propose that conflicting visual representations across chemistry and biology courses may lead to conflicting conceptual resources about ATP and bonding, and we provide a starting point for future work investigating the impact of these visual differences on student knowledge.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## ORCID

*Mingyu Yang* https://orcid.org/0000-0003-2558-7074
*L. Kate Wright* https://orcid.org/0000-0001-7379-0224
*Dina L. Newman* https://orcid.org/0000-0002-2983-1102

## REFERENCES

1. American Association for the Advancement of Science. Vision and Change in Undergraduate Biology Education: A Call to Action. 2009 https://doi.org/10.1016/S0360-3016(96)80013-7
2. Kaldaras L, Akaeze HO, Krajcik J. Developing and validating an next generation science standards-aligned construct map for chemical bonding from the energy and force perspective. J Res Sci Teach. 2023;61(7):1689–726. https://doi.org/10.1002/tea.21906
3. National Research Council. A framework for K-12 science education: practices, crosscutting concepts, and core ideas. A framework for K-12 science education: practices, crosscutting concepts, and Core ideas. Washington, DC: National Academic Press; 2012. https://doi.org/10.17226/13165
4. Cooper MM, Klymkowsky MW. The trouble with chemical energy: why understanding bond energies requires an interdisciplinary systems approach. CBE Life Sci Educ. 2013;12(2):306–12. https://doi.org/10.1187/cbe.12-10-0170
5. Goldring H, Osborne J. Students' difficulties with energy and related concepts. Phys Educ. 1994;29(1):26–32. https://doi.org/10.1088/0031-9120/29/1/006
6. Lancor RA. Using student-generated analogies to investigate conceptions of energy: a multidisciplinary study. Int J Sci Educ. 2014;36(1):1–23. https://doi.org/10.1080/09500693.2012.714512
7. Kohn KP, Underwood SM, Cooper MM. Energy connections and misconnections across chemistry and biology. CBE Life Sci Educ. 2018;17(1):1–17. https://doi.org/10.1187/cbe.17-08-0169
8. Barker V, Millar R. Students' reasoning about basic chemical thermodynamics and chemical bonding: what changes occur during a context-based post-16 chemistry course? Int J Sci Educ. 2000;22(11):1171–200. https://doi.org/10.1080/09500690050166742
9. Boo HK. Students' understandings of chemical bonds and the energetics of chemical reactions. J Res Sci Teach. 1998;35(5):569–81. https://doi.org/10.1002/(SICI)1098-2736(199805)35:5<569::AID-TEA6>3.0.CO;2-N
10. Galley WC. Exothermic bond breaking: a persistent misconception. J Chem Educ. 2004;81(4):523–5. https://doi.org/10.1021/ed081p523
11. Dreyfus BW, Sawtelle V, Turpen C, Gouvea J, Redish EF. Students' reasoning about "high-energy bonds" and ATP: a vision of interdisciplinary education. Phys Rev ST Phys Educ Res. 2014;10(1):1–15. https://doi.org/10.1103/PhysRevSTPER.10.010115
12. Lipmann F. Metabolic generation and utilization of phosphate bond energy. Adv Enzymol Relat Areas Mol Biol. 1941;1(99):381–3. https://doi.org/10.4159/harvard.9780674366701.c141
13. Franovic CGC, Williams NR, Noyes K, Klymkowsky MW, Cooper MM. How do instructors explain the mechanism by which ATP drives unfavorable processes? CBE Life Sci Educ. 2023;22(4):1–16. https://doi.org/10.1187/cbe.23-05-0071
14. Gayford CG. Some aspects of the problems of teaching about energy in school biology. European J Sci Educ. 1986;8(4):443–50. https://doi.org/10.1080/0140528860080410
15. Novick S. No energy storage in chemical bonds. JBiolog Educ. 1976;10(3):116–8. https://doi.org/10.1080/00219266.1976.9654072
16. Storey RD. Textbook Errors & Misconceptions in biology: cell structure. American Biol Teacher. 1990;52(4):213–8. https://doi.org/10.2307/4449087
17. Villafañe SM, Loertscher J, Minderhout V, Lewis JE. Uncovering students' incorrect ideas about foundational concepts for biochemistry. Chem Educ Res Pract. 2011;12(2):210–8. https://doi.org/10.1039/c1rp90026a
18. Liaw SH, Eisenberg D. Structural model for the reaction mechanism of glutamine synthetase, based on five crystal structures of enzyme-substrate complexes. Biochemistry. 1994;33(3):675–81. https://doi.org/10.1021/bi00169a007
19. Hammer D. More than misconceptions: multiple perspectives on student knowledge and reasoning, and an appropriate role for education research. American J Phys. 1996;64(10):1316–25. https://doi.org/10.1119/1.18376
20. Hammer D. Student resources for learning introductory physics. American J Phys. 2000;68(S1):S52–9. https://doi.org/10.1119/1.19520
21. Smith JP, diSessa AA, Roschelle J. Misconceptions reconceived: a constructivist analysis of knowledge in transition. J Learn Sci. 1994;3(2):115–63. https://doi.org/10.1207/s15327809jls0302_1
22. Quillin K, Thomas S. Drawing-to-learn: a framework for using drawings to promote model-based reasoning in biology. CBE Life Sci Educ. 2015;14(1):1–16. https://doi.org/10.1187/cbe.14-08-0128
23. Kozma R. The material features of multiple representations and their cognitive and social affordances for science understanding. Learn Instruct. 2003;13(2):205–26. https://doi.org/10.1016/s0959-4752(02)00021-x
24. Linenberger KJ, Bretz SL. Generating cognitive dissonance in student interviews through multiple representations. Chem Educ Res Pract. 2012;13(3):172–8. https://doi.org/10.1039/c1rp90064a
25. Hinze SR, Williamson VM, Deslongchamps G, Shultz MJ, Williamson KC, Rapp DN. Textbook treatments of electrostatic potential maps in general and organic chemistry. J Chem Educ. 2013;90(10):1275–81. https://doi.org/10.1021/ed300395e
26. Nyachwaya JM, Gillaspie M. Features of representations in general chemistry textbooks: a peek through the lens of the cognitive load theory. Chem Educ Res Pract. 2016;17(1):58–71. https://doi.org/10.1039/c5rp00140d

27. Nyachwaya JM, Wood NB. Evaluation of chemical representations in physical chemistry textbooks. Chemistry Education Research and Practice. 2014;15(4):720–8. https://doi.org/10.1039/c4rp00113c
28. Thompson B, Bunch Z, Popova M. A review of research on the quality and use of chemistry textbooks. J Chem Educ. 2023;100:2884–95. https://doi.org/10.1021/acs.jchemed.3c00385
29. Wright LK, Cardenas JJ, Liang P, Newman DL. Arrows in biology: lack of clarity and consistency points to confusion for learners. CBE Life Sci Educ. 2018;17(1):ar6. https://doi.org/10.1187/cbe.17-04-0069
30. Wright LK, Grace GE, Newman DL. Undergraduate textbook representations of meiosis neglect essential elements. Am Biol Teach. 2020;82(5):296–305. https://doi.org/10.1525/abt.2020.82.5.296
31. Simon SM, Meldrum H, Ndung'u E, Ledley FD. Representation of industry in introductory biology textbooks: a missed opportunity to advance stem learning. CBE Life Sci Educ. 2018;17(4):1–13. https://doi.org/10.1187/cbe.17-03-0057
32. Thomas DR. A general inductive approach for analyzing qualitative evaluation data. American J Eval. 2006;27(2):237–46. https://doi.org/10.1177/1098214005283748
33. Carletta J. Assessing agreement on classification tasks: the kappa statistic. Comput Linguist. 1993;22(2):249–54.
34. Cohen J. A coefficient of agreement for nominal scales. Educ Psychol Meas. 1960;20(1):37–46. http://epm.sagepub.com

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Yang M, Armpriest BC, Wright LK, Newman DL. Visual representations of energy and chemical bonding in biology and chemistry textbooks: A case study of ATP hydrolysis. Biochem Mol Biol Educ. 2025;53(3):274–85. https://doi.org/10.1002/bmb.21894