

## Leveraging Student Misconceptions to Improve Teaching of Biochemistry & Cell Biology

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### ABSTRACT

Students come to science class with many ideas of how the natural world works, some of which do not match the consensus of the scientific community and can lead to misunderstandings. Because a growing body of educational research indicates that these misconceptions can serve as resources for learning, we developed a four-point plan to leverage knowledge of common misconceptions to improve classroom teaching by refining instructional focus, providing opportunities for reflective practice, applying evidence-based practices, and promoting exploration of learning theories. By sharing this plan with our teaching colleagues, we were able to foster a collaborative approach to our and others' practice. To do this, we compiled a resource bank of common student misconceptions using data collected from the University of Toronto's National Biology Competition, developed a guide for using this misconception resource bank to promote best teaching practices, then shared this plan with our teaching colleagues in order to foster a collaborative approach to our pedagogy. In this article, we present the resource bank and guide and provide teaching tips that can be applied to a wide array of scientific course types and educational levels.

**Key Words:** assessment; biochemistry; biology education; cell structure and processes; misconceptions; teaching tips.

### ○ Introduction

Students come to science class with many ideas of how the world works (Driver et al., 1994). Some of these ideas do not match those accepted by the majority of the scientific community and can lead to misunderstandings (Ausubel et al., 1978). These ideas have been well studied and go by many names in the literature (Piaget & Inhelder, 1929; Clement et al., 1989; Sadler, 1998; Maskiewicz & Lineback, 2013). In this article we will use the term *misconception* to refer to “scientifically inaccurate understandings that students have developed about natural phenomena” (Fisher et al., 2011, pp. 418–419). Despite

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misconceptions being viewed as barriers to learning (Ausubel et al., 1978; Fuchs & Arsenault, 2017), research indicates that development of misconceptions is a natural part of learning any scientific discipline and can be leveraged to promote the learning process (Maskiewicz & Lineback, 2013; Elliott & Pillman, 2016; Chen et al., 2020). As Sadler and Sonnert state, “learning is as much about unlearning old ideas as it is about learning new ones,” so teachers must be prepared to identify which old ideas (e.g., misconceptions) must be unlearned in order to guide students through the challenging process of replacing ideas that already make sense to them with more unfamiliar, yet more scientifically accurate new ideas (Sadler & Sonnert, 2016, p. 26). Therefore, providing teachers tools to recognize and respond to common misconceptions is an important part of promoting best practices in the classroom (Phelan, 2016).

By far, the best way to learn about misconceptions for classroom use is talking with students (Smith & Tanner, 2010). However, a number of factors may preclude teachers from developing effective strategies for managing misconceptions in the classroom. To begin, the amount of information available (e.g., Duit [2009] lists >8000 misconception articles) can be overwhelming, and not all publications provide references where more crucial information about how to address the misconception can be found. Additionally, the majority of biology education research focuses on four-year universities, with little focus on secondary schools or community colleges (Schinske et al., 2017). And, as indicated in Supplemental Table 2 of our resource bank (see Supplemental Material available with the online version of this article), the existing body of research on this topic originated in only 10 countries (Australia, England, Greece, Israel, New Zealand, Singapore, Spain, Sweden, Turkey, and the United States), with no articles representing

**Table 1. Student results from the National Biology Competition 2001 Question 22. Percentages of student response are in parentheses after each multiple-choice item. The correct answer is underlined, and the misconception item is in bold. All exams can be found online (University of Toronto, 2019).**

2001, Q22. What two characteristics make water different from most other compounds?	
a. <u>Its solid state is less dense than its liquid state, and it takes up large amounts of heat to change to its gaseous state.</u> (47%)	b. <b>Its solid state is less dense than its liquid state, and it takes up only small amounts of heat to change to its gaseous state.</b> (29%)
c. Its solid state is more dense than its liquid state, and it takes up large amounts of heat to change to its gaseous state. (12%)	d. Its solid state is more dense than its liquid state, and it takes up only small amounts of heat to change to its gaseous state. (9%)
e. Its solid state is just as dense as its liquid state, and it takes up no heat to change to its gaseous state. (1%)	Blank. (3%)

Notes: While 47% of respondents answered the question correctly, 53% answered incorrectly; 29% of all students chose item b, so 55% of all incorrect responses were item b. Therefore, 55% of all the students choosing a wrong answer chose a single distractor (misconception strength = 0.55). This is a misconception item (i.e., misconception strength > 0.5).

a Canadian perspective. The lack of representation of other schooling systems and student populations may obscure regional differences in common misconceptions and disadvantage educators from other countries or those serving international or indigenous students from underrepresented countries. For example, in most provincial Canadian school systems, general grade 9 and 10 science courses are required before subject-specific courses such as biology are pursued. These courses could influence senior biology conceptions, since grade 9 and 10 science teachers are not always required to be subject-specific experts in Canada (Tippet & Milford, 2019) and the curriculum at this stage is more open for teacher autonomy than senior ones (e.g., Ontario Ministry of Education, 2008; British Columbia Ministry of Education, 2018). Additionally, Canadian science education privileges science-technology-society-environment (STSE) perspectives as a number one priority (Council of Ministers of Education, Canada, 1997), in contrast to other educational systems such as the U.S. *Next Generation Science Standards* (which places STSE in appendix J; NGSS Lead States, 2013). This leads teachers to focus on different concepts and contexts that may also influence students' conceptions in biology. As evidence that Canadian students harbor unique misconceptions in addition to those that are common across global regions, our study revealed two misconceptions unique to Canadian students that had not been noted in nearly 30 previously published articles.

Given the factors noted above, we developed a resource bank of secondary biology misconceptions that narrows the scope in relation to previous work while expanding the diversity of student populations represented in the academic literature on the subject by adding a Canadian perspective. From there, we developed a guide and four teaching strategies to leverage the information presented in the resource bank. In this article, we describe the resource bank and share teaching strategies that worked for us to target common misconceptions by providing (1) instructional focus, (2) opportunity for reflective practice, (3) examples of evidence-based practices, and (4) opportunities to explore learning theories. By describing how these resources can aid secondary biology teachers and foster a collaborative and iterative approach to teaching, we aim to improve instruction. This has wide potential

related to future disciplinary engagement (Kitts, 2009) and racial/ethnic workforce disparities (Fuchs et al., 2015).

## ○ Data Source & Analysis

To identify misconception items for our resource bank, we analyzed individual components of multiple-choice questions from the University of Toronto's National Biology Competition (NBC) from a 24-year period (1995–2018). The NBC exam contains 50 multiple-choice questions (with five items each) that test knowledge, understanding, and application of biology via a self-selected and voluntary assessment administered annually to secondary school students (ages 14–18) at participating schools. It is considered a high-quality, consistent, and rigorous test in Canada. Although this exam is not constructed for the purpose of identifying or addressing misconceptions, the large amount of data covering a broad range of topics that it provides makes it a highly useful tool for investigating misconceptions that may exist among Canadian test-takers.

To find misconception items from the NBC test data, we emulated the methods of Sadler and Sonnert (2016) and sought the most common wrong answers given by students in a multiple-choice test (Table 1). In contrast to Sadler and Sonnert (2016), who used this method to validate misconception questions they made, we analyzed existing (potentially non-misconception) items and compared these items with the misconception literature to refine our resource bank and identify novel misconceptions. This was done to ensure that we were not simply adding a list of misconceptions to the already saturated literature, but instead were narrowing our focus to only those misconceptions that apply to diverse students in order to maximize the impact of our subsequent work toward addressing the misconceptions that are most widely observed.

The NBC sample contained 114,671 students and 1230 multiple-choice questions. Among these questions, we found 134 misconception items (11%). That is, 50% or more of the students preferred one particular wrong answer on 134 questions. Of these,

**Table 2. A portion of the misconception resource bank. Misconception-item questions from the National Biology Competition, overall concept, specific misconceptions, and references where the misconceptions were reported are listed.**

Cell Structure and Processes			
Year-Question	Concepts	Misconceptions	References
1999-Q7; 2004-Q31; 2006-Q8; 2015-Q2	Membrane transport	<ul style="list-style-type: none"> <li>• Diffusion occurs quickly<sup>1</sup></li> <li>• Passive diffusion alone (without channel proteins) can move ions across a cell membrane at biologically significant rates<sup>2</sup></li> <li>• Osmosis occurs through active transport<sup>2,3</sup></li> <li>• Membrane fluidity is of little/no importance to the function of the cell membrane<sup>3,4</sup></li> <li>• All small materials can pass through a cell membrane<sup>5</sup></li> <li>• Particles actively seek (want) isolation or more room<sup>5,6</sup></li> </ul>	<sup>1</sup> Vogel, 1994 <sup>2</sup> Storey, 1992 <sup>3</sup> Rundgren & Tibell, 2010 <sup>4</sup> Storey, 1990 <sup>5</sup> Fisher et al., 2011 <sup>6</sup> Odom, 1995; Odom & Barrow, 1995, 2007

21 were analyzed in detail for this study; 16 had been previously identified in the current body of literature, and two of the other five were determined to be novel misconceptions. Results from the NBC 2001-Q22 are provided in Table 1 as an example outlining the method we employed to identify misconception items. A full review of this method can be found elsewhere (Fuchs & Arsenault, 2017).

### ○ Pairing Misconception Items with Misconceptions from the Literature

Ten subject areas were analyzed to find misconception items: General Biochemistry, Cell Structure and Processes, Cell Metabolism, Genetics, Evolution, Biological Diversity, Plant Structure and Function, Vertebrate Structure and Function, Ecology, and Hot Topics (current biology-related topics prevalent in the news). However, a full analysis of all the questions was deemed too large for this study. To pair our misconception items to misconceptions from the literature, we narrowed our analysis to include only General Biochemistry (GB) and Cell Structure and Processes (CSP). Of 1230 questions analyzed, 78 were from GB and 117 from CSP; four from GB (5%) and 17 from CSP (15%) contained misconception items. Misconceptions from GB include statements about bond type and formation, state change, and protein stability; misconceptions from CSP refer to biological orders of magnitude, presence of a nucleus, cell size, mitochondria, chloroplast and DNA, membrane transport, taxonomy, vesicle function, gene regulation, and RNA synthesis. Before adding misconceptions to our resource bank, we checked the correctness of the questions associated with misconceptions, removing those we felt were unclear (Supplemental Table 3; Clerk & Rutherford, 2000).

After vetting the questions, we searched several online databases (e.g., ERIC and Google Scholar; Duit, 2009), selecting published and unpublished sources (e.g., dissertations) and online repositories (e.g., MOSART, 2011; AAAS, 2017) for plausible misconceptions that could be inferred from the NBC misconception items. If no misconception previously identified in the literature could be paired with a misconception item, a novel misconception was

suggested. Several experienced teachers then vetted results for clarity, relevance, and accuracy.

### ○ Content of the Resource Bank

The resource bank is provided in the Supplemental Material. It contains three interrelated parts: (1) a table that highlights the misconception items identified from the NBC, associated literature-recognized misconceptions, and references where the misconceptions were reported (a portion of this table is presented in Table 2); (2) the misconception questions themselves, sorted by subject area and year, with percentage of student response given beside each multiple-choice item; and (3) information on the references from part 1 (e.g., sample size, age range, location, and methodology). To search the resource for concepts that match learning objectives, key words or phrases can be used. For example, searching for “membrane” will identify several misconceptions related to membrane processes generally, questions that highlight them, and articles in which they are discussed. All of these resources can be used separately or together to direct practice, supporting multiple teaching modalities depending on teachers’ preferences.

### ○ Informing Pedagogy

One effective way to use the misconception resource bank is to first gauge students’ prior knowledge by presenting several related misconceptions, then allow students to discuss these ideas in small groups and propose corrections to the misconceptions. This discussion-based teaching could be employed for the entire lesson as students research, debate, and are guided to the scientifically accepted answer. Alternatively, after some discussion, a lecture-based lesson could be given using students’ previous conversations as a pointer for the presentation. Here, the key words or concepts related to the misconceptions would be used to design, modify, or direct the presentation before the lesson. On the other hand, the questions from which the misconception were identified could be given as “clicker” questions, being projected for the whole class to

gauge understanding mid-lesson, at the end of the lesson, or at the beginning of the next lesson.

## ○ Instructional Focus

Similarities between misconceptions and misconception items were grouped in the resource bank to highlight repeat concepts. Although any one of the misconceptions could provide a focus for instruction, we found repeated concepts important to consider due to their presence through decades of test data. As an example, 1999-Q7, 2004-Q31, 2006-Q8, and 2015-Q2 all highlight student misconceptions about membrane transport (Supplemental Table 4). Together, they reveal that some students do not know the importance of membrane fluidity to membrane function and that others think that all small or all charged materials can pass through a cell membrane by passive diffusion. Also, some do not understand the general speed of diffusion, believing that 20 minutes would be enough time for passive diffusion to occur across a cell membrane (Vogel, 1994). Finally, several questions revealed a common misconception with regard to the “intent” of a particle, with some students thinking that particles actively seek more room regardless of constraints like size, charge, or time frame (Odom, 1995; Odom & Barrow, 2007). Because concepts related to membrane transport consistently recurred in our analysis, we found that this area of secondary biology deserved particular focus. In our practice, this resulted in more efficient lesson planning and, ultimately, improved pedagogy as we learned more about the concepts ourselves. Possible ways to address these misconceptions can be found following the references in the resource bank.

## ○ Reflective Practice

After finding a focus, reflecting on our own practice was a useful first step to address the misconceptions, as it allowed us to highlight personal pedagogical practices that propagated the ideas we sought to address. For example, three of the questions we analyzed highlighted student misconceptions with biological orders of magnitude. Specifically, some students do not know the size difference between various macromolecules and organelles (e.g., indicating that mitochondria are smaller than ribosomes or that ribosomes are smaller than proteins). Thinking about how we were propagating these misconceptions, we realized that our common teaching activity of showing a cell with all organelles and macromolecules visible and not to scale could be a culprit. Taking that activity into account, we had students in small groups reference textbook animal cell diagrams to locate and label organelles within two different human cells. Using microscope slides of skeletal muscle cells (due to their high counts of mitochondria) and pancreatic cells (due to the recent class focus on diabetes), students first viewed the cells under a compound light microscope at 40 $\times$ , 100 $\times$ , and 400 $\times$  magnifications. Other cells could have been used (e.g., hepatocytes) depending on the classroom focus, but it was important in this context to ensure that the cells had at least some visible cellular components (e.g., a nucleus) and that later visualizations of the cells, once magnified, showed structures of interest (e.g., an adipocyte would show comparatively fewer intracellular features than

a hepatocyte at high magnification). Students then sketched the two cell types, labeling visible structures as they went, before comparing diagrams within and across groups. Next, photos of these cells were shown to the entire class at increasing light-microscope magnification and then from an electron micrograph (EM) with appropriate labels using public domain images from the Dartmouth College Electron Micrograph Facility (2019) and others from histology websites (e.g., Longnecker, 2014). Using the EM images, mitochondria were clearly visible in the muscle cells, and mitochondria as well as ribosomes on the rough endoplasmic reticulum were visible in the pancreatic cells. Finally, students' diagrams and the cell images presented were compared to the original textbook examples, where differences and similarities were highlighted, and pros and cons of each visualization technique were discussed.

We found that this addition to our practice prompted our students to recognize the shape and scale difference between a “perfect” textbook example and the real thing. By incorporating direct instruction and class discussion about visualization techniques in biology, with an emphasis on the scale and shape of cells as seen by the varying images, students were able to note the vastly different sizes between cellular structures. This activity, prompted by reflective practice, eventually allowed us to branch into related topics like different sizes of macromolecules and other organelles and why these differences were so crucial to the functioning of cells, tissues, and organs.

## ○ Evidence-Based Practices

Although reflecting on our own teaching experiences proved useful in refining lessons for some misconceptions, for others we relied on the references in the resource bank to learn more about evidence-based practices. For example, when designing a unit on protein synthesis, we noted students' difficulties understanding the dynamics of protein stability. Specifically, some students think that proteins always remain in a fixed, folded state once synthesized. To address misconceptions about protein stability, activity, and structure, we adopted evidence-based teaching strategies from Robic (2010). One included focusing on differences in the way terms like *stability* are used when describing proteins as compared to their other meanings in everyday life. For example, stability is often equated to how long something may last, implying a passage of time and a kinetic property. However, *protein stability* is understood not only as a kinetic property, but as a thermodynamic one as well (Sanchez-Ruiz, 2010). Clarifying which definition of stability was used was a good first step in our instruction (Robic, 2010). Likewise, we found that discussing protein stability in terms of thermodynamics helped students view proteins as dynamic collections of folded and unfolded conformations balanced in equilibrium. As Robic (2010) argues, and as we found, this view clearly highlights that proteins are not static and unchanging after synthesis but rather respond to their environment in predictable ways. Additional evidence-based teaching practices that can serve as useful complementary approaches to addressing misconceptions include active-learning exercises such as think-pair-share and real-time writing exercises, structured worksheets, and cooperative learning activities, all accompanied by frequent formative feedback and low-stakes assessments (Connell et al., 2017).

## ○ Exploring Learning Theories

While we engaged in the strategies mentioned above, we were gradually exposed to different learning theories we could explore in our classroom. One of particular interest to us was the coexistence claim by Potvin (2017), which states that a plurality of concepts always exists at one time in an individual and these concepts can compete with each other. Evidence for this comes from neuroimaging and chronometry research (Babai & Amsterdamer, 2008; Shtulman & Valcarcel, 2012; Potvin et al., 2015) showing that more time is needed to correctly answer a scientific problem containing a misconception than one that does not (i.e., the misconception has persisted and interferes with the correct answer). We were drawn to the coexistence claim because >50% of the misconception items we studied represented repeat concepts; misconceptions related to membrane transport alone accounted for ~20% of misconception items.

In our practice, the coexistence claim brings up exciting avenues for pedagogy. For example, in our analysis, we noted student difficulty with bond formation (Boo, 1998). This difficulty, noted by others as well, could be partly due to ambiguity around why bonds occur in the first place, with regard to free energy/entropy (Boo, 1998). As Boo (1998) indicates, some students view bonding from the perspective of human relations – where an input of energy is needed to forge a relationship. In a chemistry context, however, bonding releases energy. This release of energy, and why it occurs, is foundational to understand subsequent chemical bonding concepts. Using the coexistence claim as a framework, a useful first step for instruction would be comparing and contrasting the human and chemical perspectives of bonding, and noting when, why, and in which context they ought to be applied or inhibited.

Exploring the coexistence claim was a useful way to improve our pedagogy. It provided one theory to explain why certain misconceptions may generally be difficult to address (cf. Chi, 2005). Additionally, it provided us with different ways to think about teaching and learning in science. Although we are just beginning to explore more ways to utilize this theory in our practice, we found that exploration in general increased the iterative nature of our teaching, promoting further reflective practice and exploration of evidence-based practices.

## ○ Fostering Collaboration

We were naturally prompted to share the strategies mentioned above with our grade and course partners and found that in doing so, a good portion of them became increasingly interested in the resource bank. This interest fostered a collaborative and iterative approach toward improving our teaching practice in general and lessons specifically. Collaboration in teaching has long been recognized as valuable to teachers' practice (Hargreaves, 1992; Shulman & Sherin, 2004), and the resource bank and teaching strategies gave us a starting point and common language for sharing and refining our teaching as a form of in-school professional development.

For us, the most fruitful collaboration came from engaging in professional development similar to the Lesson study or Learning study (Ko, 2019), which are related approaches originating in

Japan (Stigler & Hiebert, 1999; Yoshida, 1999) and Hong Kong (Elliott, 2015; Pang & Marton, 2003; Pang & Runesson, 2019), respectively. We, and other colleagues, used collaborative and iterative cycles of planning, teaching, and reflection to focus on our shared goal of promoting student learning. Specifically, we were committed to addressing common misconceptions students possess. These cyclical approaches allowed for rich insights into possible reasons why our teaching strategies were working (or not), and were typically accompanied by a pre/post set of questions providing additional evidence on our strategies' effectiveness (Tan & Nason, 2013). We found conversations surrounding the coexistence claim particularly fruitful in Learning study, as they provided additional lenses with which we could view our practice (Tan et al., 2019). To our knowledge, very few learning theories have been employed in Learning study (Runesson, 2016). In addition to arguing for increased collaboration in teaching, we suggest that the coexistence claim (Potvin, 2017) deserves further research, not only to contribute to the improvement of teachers' practice, but to diversify the literature on teachers' uses of theoretical concepts.

## ○ Conclusion

The objectives for this paper were to present four ways of informing and improving classroom teaching that might be useful to secondary biology, community college, and four-year university instructors who aim to target common misconceptions. Additionally, we showed that by sharing these ways of improving instruction with colleagues, a collaborative approach to teaching can be fostered that supports the development of knowledge growth and further positive changes in practice. To support these instructional tips, we described the construction of a resource bank of misconceptions in secondary biology. The resource bank described here is significant in that it confirms certain misconceptions' prevalence in student populations and narrows the very large field of secondary biology misconceptions described in previous work.

## ○ Suggestions for Future Research

Two questions from the NBC, 2003-Q19 and 2005-Q6, contained misconception items we could not pair with existing misconceptions. 2003-Q19 indicates that some students think vesicles pass through the plasma membrane rather than fusing with it. This process increases the surface area of the cell and allows proteins previously interior to the vesicle to be exterior to the cell. 2005-Q6 indicates that some students confuse gene regulation and the connection to redox reactions (e.g., methylation and acetylation for gene silencing, which turn the genes "on/off") with transcription factors (proteins that have DNA binding domains and control rates of transcription). Further research should be conducted on misconceptions related to vesicle transport and gene regulation.

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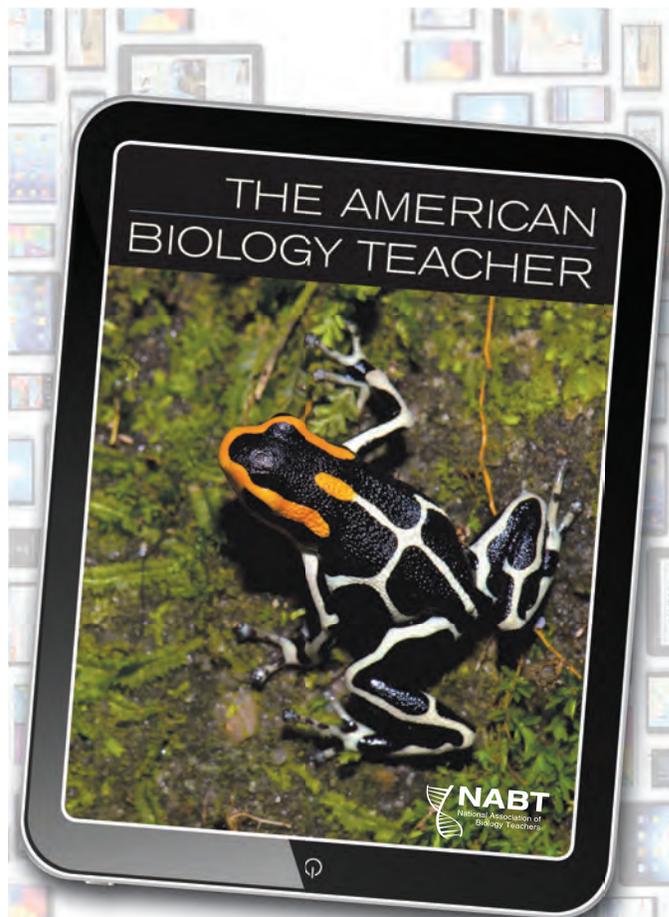
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