Secondary biology misconceptions: using 23 years of test-data to inform pedagogy.

Travis T. Fuchs
The University of British Columbia
West Point Grey Academy

Mike Arsenault
Lakefield College School

Manuscript proceedings for the 2018 National Association of Biology Teachers Professional Development Conference, 10th Annual NABT Biology Education Research Symposium

Abstract: Students come to science class with many ideas of how the world works. Of all the ideas, some do not match those held by the scientific community and can lead to misunderstandings. These ideas go by many names in the literature, but for this paper we will call them misconceptions. Contemporary educational research views misconceptions as resources for learning, and as such, we compiled a list of common student misconceptions to guide our practice. Using the University of Toronto's National Biology Competition, we analyzed test-data from 111, 238 students, and 1,181 questions over 23 years (1995-2017), finding 130 misconception questions throughout the data set. We will present 18 of these misconceptions from the subject areas General Biochemistry and Cell Structure and Processes. We will also highlight how the misconceptions identified can be used to inform pedagogy.

Keywords: conceptions; biology education; science education; school science

Fuchs, T.T., & Arsenault, M. (2018). Secondary biology misconceptions: using 23 years of test-data to inform pedagogy. Conference proceedings of the National Association of Biology Teachers Professional Development Conference, 10th Annual NABT Biology Education Research Symposium, San Diego, California.

INTRODUCTION

Students come to science class with many ideas of how the world works (Driver et al., 1994). Some of these ideas may be completely correct or even beyond the knowledge of a particular course. Of all the ideas, some do not match those of the scientific community and can lead to misunderstandings (Ausubel, Novak, & Hanesian, 1978; D'Avanzo, 2008; Sadler, 1998). These ideas have been well documented and studied (Coley & Tanner, 2012; Driver et al., 1994; Galvin, Simmie, & O'Grady, 2015; Piaget & Inhelder, 1929; Treagust, 1988) and go by many names in the literature including misconceptions (Modell, Michael, & Wenderoth, 2005), pre-conceptions (Clement, Brown, & Zietsman, 1989), alternative conceptions (Tanner & Allen, 2005), and children's science (Gilbert, Osborne, & Fensham, 1982). However, all of these terms are connected by the inconsistency found between a learner's explanation of a specific scientific phenomenon and that of the scientific community (Gilbert & Watts, 1983). For this paper, we will call these ideas misconceptions as outlined by Sadler (1998).

Misconceptions can be viewed as barriers to learning (Ausubel, Novak, & Hanesian, 1978). When exhibited by teachers, they can undermine effective pedagogy (ibid). When exhibited by students, the can be difficult to correct (Schneps & Sadler, 1989) and can affect the learning of other related disciplines (Kumandaş, Ateskan & Lane, 2018). That being said, contemporary education literature views misconceptions as resources for learning (Elliott & Pillman, 2016; Karpudewan, Zain, & Chandrasegaran, 2017; Kumandaş, Ateskan & Lane, 2018). Since they seem to be a natural part of learning any scientific discipline (Sadler et al., 2009), misconceptions should not be fought against or seen as barriers. Rather, once misconceptions are known, they can be planned for and addressed (Phelan, 2016). As such, we sought to compile a reference guide of misconceptions from secondary biology we could use to more effectively plan our lessons and assessments. Bettering scientific instruction has wide potential, from addressing systemic trends of racial/ethnic disparities in the work force (Fuchs, Sadler & Sonnert, 2015), to considering student scientific identity and future engagement with the discipline (Kitts, 2009).

Objectives

Lists of common student misconceptions are not novel and there has been a tremendous amount of work and dedication to their construction (American Association for the Advancement of Science, 2017; D'Avanzo, 2008; Driver et al., 1994; Duit, 2009; MOSART, 2011). On the whole, they provide educators with difficult concepts to focus their instruction (D'Avanzo, 2008) and as such, many currently exist in biology at the college level (Abraham et al., 2014; Anderson et al., 2002; Shi et al., 2010) and K-12 level (Sadler et al., 2013; MOSART, 2011).

Although some reference guides for misconceptions do deal solely with secondary biology, we were left wanting for more information and a Canadian perspective, if not sample. Specifically, based on our review of the literature, we found not all studies provide references of other research where more information can be found. This has two important implications. First, the references often provide examples of how the misconception can be addressed. Even with direct instruction, certain misconceptions persist (Fisher, Williams, & Lineback, 2011; Potvin et al., 2015; Odom & Barrow, 2007). Simply knowing of it may not be enough to address it in the classroom without guidance and recommendations. Second, the references can provide insights into personal pedagogical practices which propagate the ideas an educator seeks to address. Taking this information into account, the main objectives for our project were to:

1. Make a reference guide of misconceptions for the subject areas General Biochemistry (GB) and Cell Structure and Processes (CSP).
2. To highlight the guides usefulness to inform pedagogy.

METHODS

Data Sources

To identify the misconceptions that make up our list, we analyzed test-data from the University of Toronto's National Biology Competition (NBC) for a 23-year period in Microsoft's Excel. The NBC sample contained 111,238 students and 1,181 multiple-choice questions from 1995-2017. Each question had five items and contained only one correct answer. In determining the exam score for each student, there was a penalty assigned for each incorrect response, and no penalty for leaving a question blank.

The NBC is a paid ($7 CAD per student in 2017), self-selected assessment administered annually in April at participating schools. The assessment aims to test participants' understanding and application of biology. The competition is open to secondary school students (ages 14-18) and requires no prerequisites to write. Most participants from Canada are from schools in Ontario (about 70%), but schools from outside Canada also participate. Since 2014, exam results are presented separately for schools within Canada and schools outside of Canada. Our results use the data from Canadian schools for 2014-2017.

Experts in the field of biology and science education compose the 50 questions on each NBC exam. A subject expert other than the question writer also reviews each question. The competition director is a university faculty member and has provided the same guidelines to question-writers from 1995-2017; the director also assembles the final exam and grades the exam. Because of this consistency and rigor, the NBC was deemed a high-quality test worthy of study.

Initial Analysis

To find misconception questions and items from the NBC test-data, we emulated the methods of Sadler & Sonnert (2016) and sought the most common wrong answers given by students in a multiple-choice test. For the item to be labelled a misconception, greater than 50% of students had to choose the same wrong answer (Table 1). While Sadler & Sonnert (2016) used this methodology to validate misconception questions they made, our initial analysis differed. We analysed existing (potentially non-misconception) items and then compared these items with the misconception literature.

Of the 1,181 questions analyzed from the NBC, we found 130 misconception items (11%). That is, 50% or more of the students preferred one particular wrong answer on 130 questions. The 130 misconception questions all followed hallmarks of the misconception literature. They were ubiquitous across subject areas, had no correlation with question difficulty, and had a high distractive power (Fuchs & Arsenault, 2017). Also, the misconceptions identified could be found in previous misconception studies. The results from the NBC 2006-Q22 are given as an example in Table 1 outlining the methods we employed to identify misconception items.

Table 1. Student results from the National Biology Competition 2001 Question 22. Percent of student response are given beside each multiple-choice item. Correct answer is underlined, misconception item is in bold.

2001, Q22. What two characteristics make water different from most other compounds?	
a. Its solid state is less dense than its liquid state, and it takes up large amounts of heat to change to its gaseous state. 47%	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.** 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%

While 47% of respondents answered the question correctly (Table 1, item a, underlined), 53% answered incorrectly. 29% of all students chose item b (in bold), and therefore 55% (i.e., 29%/53%) of all incorrect responses were item b. Therefore, of all the students choosing a wrong answer, 55% choose a single distractor (misconception strength=0.55). This is a misconception item (i.e., misconception strength > 0.5).

Analytic Plan

In order to make the reference guide, we compared identified misconception items from GB and CSP to misconceptions from the literature. First, we checked for the correctness of the misconception questions and sorted them by subject area. Then, we searched several online databases (e.g., ERIC; Google Scholar; Duit, 2009), selecting published and unpublished sources (e.g., dissertations), and online repositories (e.g., American Association for the Advancement of Science, 2017; MOSART, 2011) for misconceptions supporting the NBC misconception items. To guide our search, we used questions like, “why might a student pick the most popular wrong answer over the correct answer?” and searched for literature-identified misconceptions that could give us an idea. Recognizing that more than one answer could be inferred from each item, we included several misconceptions in the results. After the initial analysis, results were vetted by several experienced teachers of biology for clarity, relevance, and accuracy.

Table 2. General Biochemistry and Cell Structure and Processes Reference Guide by year and question. Conceptually related questions are grouped. Questions in their entirety can be found at the University of Toronto National Biology Competition website (University of Toronto, 2018).

Year-Question	Misconception(s)	Reference
General Biochemistry		
1997-Q27	• No rules govern chemical bonding (e.g., no proper concept of electronegativity and thus no concept of electronegativity difference)[1] • Ionic bonds are a result of sharing electrons and covalent bonds are a result of transfer[1,2] • Bond type cannot be determined without ± showing[3]	[1]Boo, 1998 [2]Butts & Smith, 1987; Nicoll, 2001; Tan & Treagust, 1999 [3]Luxford & Bretz, 2014
2001-Q22	• Matter does not require heat to change state[1] • State change is caused by other phenomena (e.g., air moving particles)[2] • Difference between small and large amounts of heat is not known (e.g., changing to a gaseous state can occur at low heat levels in some substances; the amount of heat required to change water to a gaseous state is relatively high)[3]	[1]Osborne & Cosgrove,1983 [2]Tsitsipis et al., 2010 [3]Coştu & Ayas, 2005; Coştu et al., 2010
2004-Q5	• Proteins always remain in a folded state once synthesized[1] • Only the interior of proteins contain reactive side chains (R-groups)[2] • Intermolecular forces are caused by gravity[3]	[1]Robic, 2010 [2]Villafañe et al., 2011 [3]Özmen, 2004
2006-Q27	• Covalent bonds are the result of sharing one electron between two atoms[1] • Ionic bonds form neutral molecules, this neutrality results in stronger bonds[1] • A bond can be both sharing and transferring electrons at the same time[2]	[1]Boo, 1998 [2]Luxford & Bretz, 2014

Cell Structure and Processes		
1995-Q2; 2006-Q8; 2017-Q30	• Relative sizes of different atoms, macromolecules, and organelles is not known (e.g., mitochondria are smaller than ribosomes, mitochondria are smaller than proteins etc.)[1] • The different shapes of organelles is not known[1,2]	[1]Dreyfus & Jungwirth, 1988 [2]Storey, 1990
1996-Q1	• All cells have a nucleus[1]	[1]Dreyfus & Jungwirth, 1989
1997-Q4	• Energy can be used up or spent[1] • Energy is only used for obvious activities (e.g., growth or movement)[2] • Organism cell characteristics correlate to the characteristics of the organism (e.g., plants are sedentary and grow, animals move around)[3]	[1]Chabalengula, Sanders, & Mumba, 2012 [2]Duit, 2014; Fetherston, 1999; Trumper, 1997 [3]Sadler et al., 2013
1998-Q3; 2002-Q2; 2014-Q1	• Plants only contain chloroplast (no mitochondria)[1] • Plants do not have chromosomes[2] • Chloroplast do not contain DNA[3] • Mitochondria do not contain DNA[3]	[1]Storey, 1991 [2]Banet & Ayuso, 2000 [3]Elrod, 2007
1999-Q7; 2004-Q31; 2006-Q8; 2015-Q2	• Diffusion occurs quickly[1] • Passive diffusion alone (without channel proteins) can move ions across a cell membrane at biologically significant rates[2] • Osmosis occurs through active transport[2,3] • Membrane fluidity is of little/no importance to the function of the cell membrane[3,4] • All small materials can pass through a cell membrane[5] • Particles actively seek (want) isolation or more room[5,6]	[1]Vogel, 1994 [2]Storey, 1992 [3]Rundgren & Tibell, 2010 [4]Storey, 1990 [5]Fisher et al., 2011 [6]Odom, 1995; Odom & Barrow, 1995; Odom & Barrow, 2007
2002-Q10	• Bacteria are part of the domain Eukarya[1]	[1]Byrne, 2011
2016-Q6	• RNA is synthesized in the cytosol[1]	[1]Elrod, 2007; Wright et al., 2014

RESULTS AND DISCUSSION

Objective One: The Reference Guide

The reference guide can be found in Table 2 and contains misconception question year and number from the NBC, associated literature-recognized misconceptions, and references. Misconception questions in their entirety can be found at the NBC website (University of Toronto, 2018).

Of 1,181 questions analyzed, 66 were from GB and 114 from CSP. Four from GB (6%) and 14 from CSP (12%) contained misconception items. Misconceptions from GB were found through nine years of the sample and referred to bonding, energy concepts in biology, and protein stability. Misconceptions from CSP were found through 23 years of the sample and referred to biological orders of magnitude, presence of a nucleus, cellular use of energy, mitochondria, chloroplast and DNA, membrane transport, taxonomy, and RNA synthesis.

Objective Two: Informing Pedagogy

The reference guide found in Table 2 provides educators with important difficult concepts they should be aware of for planning. As an example, when designing a series of lessons around the chemical properties of water, we noted students struggle with state changes and the relative amounts of heat needed to cause the change. 2001-Q22 indicates some student do not know that large amounts of heat are required to change water from a liquid to a gas. Taking this into account, we began the lesson by reviewing various concepts related to change of state and what factors may affect this (e.g., heat, pressure, temperature, molecular characteristics). Then, we had students predict the amount of heat needed to change varying substances (both common and uncommon) from a liquid to a gas and place those substances in order from highest to lowest. During the activity, we gave careful consideration and time for students to consider and explain why they were ordering the substances as they did. Students were encouraged to share responses and make changes to their predictions as the discussion continued. After the students had solidified their predictions and explanations, we had them look up verified heat of vaporization values on-line and note any discrepancies in their ordering. This was followed by a series of discussions and internet searches as students began to explain and interpret how their ordering matched or did not match what was presented on-line. During the discussion, particular emphasis was placed on the position of water in the ordering. We hoped this activity would allow students to not only see the relatively high amount of heat required to change water form a liquid to a gas but to begin to notice other patterns in regard to specific characteristics of the substances in question (e.g., molecular shape, types of bonds). Eventually, this allowed us to branch to related concepts like intermolecular forces. Finally, we discussed how those forces might relate to other chemical properties of water.

As another example, when designing an opening unit on macromolecules and organelles, we noted students struggle with orders of magnitude in cell biology (Table 2, 1995-Q2, 2006-Q8, 2017-Q30). Reflecting on our teaching practice as a starting point, it would be reasonable to assume that the common activity of showing a cell with all organelles visible, despite their vastly different sizes, may reinforce these ideas. Taking that activity into account, we had students use textbook cell diagrams as a guide to locate organelles under a light microscope. We hoped the discussion that followed would provide a clear comparison between the scale and shape of a 'perfect' textbook example and the real thing. In addition, direct instruction about visualization techniques in biology, with an emphasis on scale and shape, was implemented. Eventually, this allowed us to branch into related topics like different sizes of macromolecules and other organelles. Although reflecting on our own experiences teaching proved useful to design lessons for some misconceptions, for others we had little experience and struggled with ways to address them. This is when the references accompanying Table 2 proved useful.

When designing a unit on protein synthesis, we noted student difficulty with protein stability. Specifically, some students think proteins always remain in a folded state once synthesized. Wanting more information, we followed the references in Table 2 to Robic (2010). In this article, a host of protein stability, activity, and structure misconceptions are presented including various ways to address them. One strategy included a focus on the difference between terms like stability when used to describe proteins vs every day. In every day, stability is often equated to how long something may last, implying a passage of time and a kinetic property. However, protein stability is not only understood as a kinetic property, but as a thermodynamic one as well (Sanchez-Ruiz, 2010). Clarifying which definition of stability is used is a good first step towards meaningful instruction (Robic, 2010). Likewise, discussing protein stability in terms of thermodynamics may help students view proteins as dynamic collections of folded and non-folded conformations balanced in equilibrium. As Robic (2010) argues, this view clearly highlights that proteins are not static and unchanging after synthesis but rather respond to their environment in predictable ways. By using the reference guide found in Table 2, we were able to plan for misconceptions through our own ideas and/or that of previous researchers. Like others, we found that this led to improved practice (D'Avanzo, 2008; Driver et al., 1994; Phelan, 2016).

CONCLUSION

Future Research

Surprisingly, over 50% of studied misconception items represented repeated concepts, with misconceptions about membrane transport representing around 20% of questions studied. Misconceptions relating to membrane transport have been examined extensively in the literature (Fisher, Williams & Lineback, 2011; Odom, 1995; Odom & Barrow, 1995; Odom & Barrow, 2007; Vogel, 1994) garnering many hypotheses as to why they are so difficult to address. However, hypotheses concerning the persistent nature of misconceptions in general has been studied comparatively less. Future research should examine persistent misconceptions, paying special attention to the effects of instructional approaches (Fisher, Williams, & Lineback, 2011; Sadler & Sonnert, 2016) and developing cognitive theories (e.g., the coexistence claim [Potvin, 2017; Potvin et al., 2015; Shtulman, & Valcarcel, 2012]) in their study. In addition, further analysis of the remaining 112 misconception questions in our entire data set is needed to see if over half of the sample represents persistent concepts.

Limitations

The multiple-choice test on which our analysis was based restricts student responses and explanations of why they chose a particular answer (Smith & Tanner, 2010). This limits the ability of our study to meaningfully inform pedagogy without follow-up interviews and additional questioning of students. Nonetheless, the misconceptions highlighted by this kind of study can still serve as a powerful starting point for educators within the context of their institution or classroom and are worthy of further analyses (to the extent possible) that may establish the suggested connections.

Conclusion

This project sought to make a reference guide of misconceptions for the subject areas General Biochemistry and Cell Structure and Processes. We have shown in our practice that the guide proved useful for planning units and lessons. In addition, the guide's accompanying references provided valuable instructional strategies and opportunities for pedagogical reflection. We believe teachers of biology can improve their practice by being aware of student explanations of scientific phenomenon that do not align with those of the scientific community. The potential for reflective practice and student learning is large and should not be ignored.

AUTHOR'S NOTE

Travis T. Fuchs is a high school science and math teacher currently pursuing doctoral work at the University of British Columbia. Email: ttf421@mail.harvard.edu Twitter: @TTHFuchs

Mike Arsenault teaches high school science at Lakefield College School and is actively involved in mentoring early career science teachers and travelling with students on global learning service projects. His students have participated in the University of Toronto National Biology Competition each year since the competition began in 1995. Email: marsenault@lcs.ca Twitter: @mrarsenault

Contributions of authors: TF and MA conceived and designed the study and analyzed the data. TF wrote the article.

Acknowledgements: We thank the many biology teachers and students we have spoken with throughout this study at West Point Grey Academy, The York School, and Lakefield College School. We especially thank Professor Corey A. Goldman, University of Toronto, who provided the raw data for this article. Corey is the founding director of the University of Toronto National Biology Competition and coordinates the composition and grading of the exam questions.

Ethical Approval: This study was approved by the University of British Columbia Research Ethics Board.

References in text

Abraham, J. K., Perez, K. E., & Price, R. M. (2014). The Dominance Concept Inventory: a tool for assessing undergraduate student alternative conceptions about dominance in Mendelian and population genetics. *CBE-Life Sciences Education, 13*(2), 349-358.

American Association for the Advancement of Science. (2017). *AAAS Science Assessment.* Retrieved October 4, 2018 from http://assessment.aaas.org/topics

Anderson, D. L., Fisher, K. M., & Norman, G. J. (2002). Development and evaluation of the conceptual inventory of natural selection. *Journal of Research in Science Teaching, 39*(10), 952-978.

Ausubel, D. P., Novak, J. D., & Hanesian, H. (1978). *Educational psychology: A cognitive view*. New York, NY: Holt, Rinehart & Winston.

Clement, J., Brown, D. E., & Zietsman, A. (1989). Not all preconceptions are misconceptions: finding 'anchoring conceptions' for grounding instruction on students' intuitions. *International Journal of Science Education*, *11*(5), 554-565.

Coley, J. D., & Tanner, K. D. (2012). Common origins of diverse misconceptions: cognitive principles and the development of biology thinking. *CBE-Life Sciences Education, 11*(3), 209-215.

D'Avanzo, C. (2008). Biology concept inventories: overview, status, and next steps. *BioScience, 58*(11), 1079-1085.

Driver, R., Squires, A., Rushworth, P., & Wood-Robinson, V. (1994). *Making sense of secondary science: Research into children's ideas.* London, UK: Routledge.

Duit, R. (2009). Bibliography STCSE: Students' and teachers' conceptions and science education. Retrieved October 6, 2018 from: http://www.if.ufrj.br/~marta/aprendizagememfisica/fv09.pdf

Elliott, K., & Pillman, A. (2016). Making science misconceptions work for us. *Teaching Science*, *62*(1), 36.

Fisher, K. M., Williams, K. S., & Lineback, J. E. (2011). Osmosis and diffusion conceptual assessment. *CBE-Life Sciences Education*, *10*(4), 418-429.

Fuchs, T. T., Sadler, P. M., & Sonnert, G. (2015). High School Predictors of a Career in Medicine. *Journal of Career and Technical Education*, *30*(1), 9-28.

Fuchs, T. T., & Arsenault, M. (2017). Using test data to find misconceptions in secondary science. *School Science Review*, *98*(364), 31-36.

Galvin, E., Simmie, G.M., & O'Grady, A. (2015) Identification of Misconceptions in the Teaching of Biology: A Pedagogical Cycle of Recognition, Reduction and Removal. *Higher Education of Social Science, 8*(2), 1-8.

Gilbert, J. K., Osborne, R. J., & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education*, *66*(4), 623-633.

Karpudewan M., Zain A. N. M., Chandrasegaran A. L. (2017) Introduction: Misconceptions in Science Education: An Overview. In: Karpudewan M., Md Zain A., Chandrasegaran A. (eds) *Overcoming Students' Misconceptions in Science*. Springer, Singapore.

Kitts, K. (2009). The paradox of middle and high school students' attitudes towards science versus their attitudes about science as a career. *Journal of Geoscience Education, 57*(2), 159–164.

Kumandaş, B., Ateskan, A., & Lane, J. (2018). Misconceptions in biology: a meta-synthesis study of research, 2000–2014. *Journal of Biological Education*, 1-15.

Modell, H., Michael, J., & Wenderoth, M. P. (2005). Helping the learner to learn: the role of uncovering misconceptions. *The American Biology Teacher, 67*(1), 20-26.

MOSART. (2011). *Misconception-Oriented Standards Based Assessment Resources for Teachers*. Retrieved October 6, 2018 from https://www.cfa.harvard.edu/smgphp/mosart/aboutmosart_2.html

Odom, A. L. (1995). Secondary & College Biology Students' Misconceptions About Diffusion & Osmosis. *The American Biology Teacher, 57*(7), 409-415.

Odom, A. L., & Barrow, L. H. (1995). Development and application of a two-tier diagnostic test measuring college biology students' understanding of diffusion and osmosis after a course of instruction. *Journal of Research in Science Teaching, 32*(1), 45-61.

Odom, A. L., & Barrow, L. H. (2007). High school biology students' knowledge and certainty about diffusion and osmosis concepts. *School Science and Mathematics*, *107*(3), 94-101.

Phelan, J. (2016). Ten Tweaks That Can Improve Your Teaching. *The American Biology Teacher*, *78*(9), 725-732.

Piaget, J., & Inhelder, B. (1929). *The child's conception of space.* (F.J. Langdon & J.L. Lunzer, Trans.) New York, NY: Norton.

Potvin, P., Masson, S., Lafortune, S., & Cyr, G. (2015). Persistence of the intuitive conception that heavier objects sink more: A reaction time study with different levels of interference. *International Journal of Science and Mathematics Education, 13*(1), 21-43.

Potvin, P. (2017). The Coexistence Claim and Its Possible Implications for Success in Teaching for Conceptual "Change". *European Journal of Science and Mathematics Education*, *5*(1), 55-66.

Robic, S. (2010). Mathematics, thermodynamics, and modeling to address ten common misconceptions about protein structure, folding, and stability. *CBE-Life Sciences Education, 9*(3),189-195.

Sadler, P. M. (1998) Psychometric Models of Student Conceptions in Science: Reconciling Qualitative Studies and Distractor-Driven Assessment Instruments. *Journal of Research in Science Teaching, 35*, 265-296.

Sadler, P., Coyle, H., Miller, J., Cook-Smith, N., Dussault, M., & Gould, R. (2009) The astronomy and space science concept inventory: Development and validation of an assessment instrument aligned with the national standards. *Astronomy Education Review, 8*(1), 1–26.

Sadler, P. M., Sonnert, G., Coyle, H. P., Cook-Smith, N., & Miller, J. L. (2013). The influence of teachers' knowledge on student learning in middle school physical science classrooms. *American Educational Research Journal, 50*(5), 1020-1049.

Sadler, P. M., & Sonnert, G. (2016). Understanding Misconceptions Teaching and Learning in Middle School Physical Science. *American Educator*, *6*, 7.

Sanchez-Ruiz, J. M. (2010). Protein kinetic stability. *Biophysical chemistry*, *148*(1-3), 1-15.

Schneps, M., & Sadler, P. M. (1989). A private universe [Video]. *Santa Monica, CA: Pyramid Film and Video.*

Shi, J., Wood, W. B., Martin, J. M., Guild, N. A., Vicens, Q., & Knight, J. K. (2010). A diagnostic assessment for introductory molecular and cell biology. *CBE-Life Sciences Education, 9*(4), 453-461.

Shtulman, A., & Valcarcel, J. (2012). Scientific knowledge suppresses but does not supplant earlier intuitions. *Cognition, 124*(2), 209-215.

Smith, J. I., & Tanner, K. (2010). The problem of revealing how students think: concept inventories and beyond. *CBE-Life Sciences Education, 9*(1), 1-5.

Tanner, K., & Allen, D. (2005). Approaches to biology teaching and learning: understanding the wrong answers—teaching toward conceptual change. *Cell Biology Education, 4*(2), 112-117.

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education, 10*(2), 159-169.

University of Toronto National Biology Competition. (2017). Past Exams. Retrieved October 5, 2018 from http://www.biocomp.utoronto.ca/past-comps/exams

Vogel, S. (1994). Dealing honestly with diffusion. *American Biology Teacher, 56*, 405-405.

References from Table 2

General Biochemistry

Boo, H. K. (1998). Students' understandings of chemical bonds and the energetics of chemical reactions. *Journal of Research in Science Teaching*, *35*(5), 569-581.

Butts, B., & Smith, R. (1987). HSC chemistry students' understanding of the structure and properties of molecular and ionic compounds. *Research in Science Education*, *17*(1), 192-201.

Coştu, B., & Ayas, A. (2005). Evaporation in different liquids: Secondary students' conceptions. *Research in Science & Technological Education*, *23*(1), 75-97.

Coştu, B., Ayas, A., & Niaz, M. (2010). Promoting conceptual change in first year students' understanding of evaporation. *Chemistry Education Research and Practice*, *11*(1), 5-16.

Luxford, C. J., & Bretz, S. L. (2014). Development of the Bonding Representations Inventory to identify student misconceptions about covalent and ionic bonding representations. *Journal of Chemical Education*, *91*(3), 312-320.

Nicoll, G. (2001). A report of undergraduates' bonding misconceptions. *International Journal of Science Education*, *23*(7), 707-730.

Osborne, R. J., & Cosgrove, M. M. (1983). Children's conceptions of the changes of state of water. *Journal of research in Science Teaching*, *20*(9), 825-838.

Özmen, H. (2004). Some student misconceptions in chemistry: A literature review of chemical bonding. *Journal of Science Education and Technology*, *13*(2), 147-159.

Robic, S. (2010). Mathematics, thermodynamics, and modeling to address ten common misconceptions about protein structure, folding, and stability. *CBE-Life Sciences Education*, *9*(3), 189-195.

Tan, D. K., & Treagust, D. F. (1999). Evaluating students' understanding of chemical bonding. School Science Review, 81(294), 75-84.

Tsitsipis, G., Stamovlasis, D., & Papageorgiou, G. (2010). The effect of three cognitive variables on students' understanding of the particulate nature of matter and its changes of state. *International Journal of Science Education*, *32*(8), 987-1016.

Villafañe, S. M., Loertscher, J., Minderhout, V., & Lewis, J. E. (2011). Uncovering students' incorrect ideas about foundational concepts for biochemistry. *Chemistry Education Research and Practice*, *12*(2), 210-218.

Cell Structure and Processes

Banet, E., & Ayuso, E. (2000). Teaching genetics at secondary school: a strategy for teaching about the location of inheritance information. *Science Education, 84*(3), 313-351.

Byrne, J. (2011). Models of Micro- Organisms: Children's knowledge and understanding of microorganisms from 7 to 14 years old. *International Journal of Science Education*, *33*(14), 1927-1961.

Chabalengula, V. M., Sanders, M., & Mumba, F. (2012). Diagnosing students' understanding of energy and its related concepts in biological content. *International Journal of Science and Mathematics Education*, *10*(2), 241-266.

Dreyfus, A., & Jungwirth, E. (1988). The cell concept of 10th graders: curricular expectations and reality. *International Journal of Science Education*, *10*(2), 221-229.

Dreyfus, A., & Jungwirth, E. (1989). The pupil and the living cell: a taxonomy of dysfunctional ideas about an abstract idea. *Journal of Biological Education*, *23*(1), 49-55.

Duit R. (2014) Teaching and Learning the Physics Energy Concept. In: Chen R. et al. (eds) *Teaching and Learning of Energy in K – 12 Education* (pp. 67-85). Springer, Cham.

Elrod, S. (2007). *Genetics concepts inventory*. Retrieved October 3, 2018 from http://bioliteracy.colorado.edu/Readings/papersSubmittedPDF/Elrod.pdf

Fetherston, T. (1999). Students constructs about energy and constructivist learning. *Research in Science Education*, *29*(4), 515-525.

Fisher, K. M., Williams, K. S., & Lineback, J. E. (2011). Osmosis and diffusion conceptual assessment. *CBE-Life Sciences Education*, *10*(4), 418-429.

Odom, A. L. (1995). Secondary & College Biology Students' Misconceptions About Diffusion & Osmosis. *The American Biology Teacher*, *57*(7), 409-415.

Odom, A. L., & Barrow, L. H. (1995). Development and application of a two- tier diagnostic test measuring college biology students' understanding of diffusion and osmosis after a course of instruction. *Journal of Research in Science Teaching*, *32*(1), 45-61.

Odom, A. L., & Barrow, L. H. (2007). High school biology students' knowledge and certainty about diffusion and osmosis concepts. *School Science and Mathematics*, *107*(3), 94-101.

Rundgren, C. J., & Tibell, L. A. (2010). Critical Features of Visualizations of Transport through the Cell Membrane: An Empirical Study of Upper Secondary and Tertiary Students' Meaning-Making of a Still Image and an Animation. *International Journal of Science and Mathematics Education*, *8*(2), 223-246.

Sadler, P. M., Coyle, H., Smith, N. C., Miller, J., Mintzes, J., Tanner, K., et al. (2013). Assessing the life science knowledge of students and teachers represented by the K–8 National Science Standards. *CBE-Life Sciences Education*, *12*(3), 553-575.

Storey, R. D. (1990). Textbook errors & misconceptions in biology: Cell structure. *The American Biology Teacher*, *52*(4), 213-218.

Storey, R. D. (1991). Textbook errors & misconceptions in biology: Cell metabolism. *The American Biology Teacher*, *53*(6), 339-343.

Storey, R. D. (1992). Textbook errors & misconceptions in biology: Cell physiology. *The American Biology Teacher*, *54*(4), 200-203.

Trumper, R. (1997). A survey of conceptions of energy of Israeli pre- service high school biology teachers. *International Journal of Science Education*, *19*(1), 31-46.

Vogel, S. (1994). Dealing honestly with diffusion. *American Biology Teacher*, *56*, 405-405.

Wright, L. K., Fisk, J. N., & Newman, D. L. (2014). DNA→ RNA: What do students think the arrow means?. *CBE-Life Sciences Education*, *13*(2), 338-348.