Utilizing Keeley's Formative Assessments in a Sophomore-level Technical Civil and Environmental Engineering Course to Identify and Address Students' Misconceptions

Dr. Natasha Andrade, University of Maryland, College Park

Dr. Natasha Andrade is a Lecturer in the Civil and Environmental Engineering Department at the University of Maryland College Park. Her responsibilities include teaching various undergraduate courses in environmental engineering (such as Engineering for Sustainability and Environmental Engineering Science) and conducting engineering education research. She has specialized in redesigning engineering courses to make them learner-centered and based on active learning activities. More recently, she started work on engineering education research that aims to effectively incorporate socio-technical thinking in required technical courses. Her discipline research is focused on the production of stabilized biosolids, its use as a fertilizer and its impact on environmental pollution concerning organic contaminants. She recently has started work on Amazonic mercury contamination due to illegal mining.

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Abstract

It is known that students, before taking engineering courses, have prior notions about natural phenomena gained in college science courses and in K-12 education. Sometimes, these prior notions may not align with currently accepted scientific knowledge and experts' knowledge [1], [2]. Bridging the gap between how students understand basic science principles and how experts understand the same principles can be a challenge. However, this challenge is worth undertaking as the understanding of basic scientific principles influence engineering practice [3].

This paper presents the results of two assessments utilized in the classroom to identify students' misconceptions. The assessments are used in a sophomore-level civil and environmental engineering technical course named Engineering for Sustainability. The course focuses on the application of knowledge gained in basic science classes to engineering problems, which is one of the ABET requirements for accreditation [4]. The course covers sizing of non-renewable and renewable energy systems, as well as design of green infrastructure for stormwater management, and sustainability rating tools. Students' ideas about greenhouse effect and energy transfer were assessed using Keeley's probes [5], [6], which are formative assessment activities designed to uncover students' concepts primarily in the K-12 grades. Although the assessment probes are not designed for post-secondary level, they have been useful in identifying engineering students' preconceived ideas.

Analysis of the data shows that between 12.3 and 38.2 % of the target student population has misconceptions with regards to heat transfer concepts. These misconceptions are rooted in their ideas of heat and cold as entities that move between objects. With regards to the greenhouse effect, the vast majority of the students showed a variety of misconceptions. The most prevalent misconception associated with the greenhouse effect is conflating it or closely relating it to the thinning of the ozone layer.

Introduction

In the research literature, misconceptions take several names. Goris and Dyrenfurth [3] provide a very good review of the terms that are used in scientific literature, which include, among others, nonscientific beliefs, alternative frameworks, p-prims. Though vocabulary may change, misconceptions (term chosen for this paper) are how people make sense of the world even though it does not reflect established scientific knowledge held by experts. Misconceptions may also be incorrect categorizations, particularly if one understands concepts as organizing knowledge in categories [7]. In general, misconceptions may arise due to incorrect instruction, but they may also be constructed by everyday interactions and language barriers. It is important to note here that there is a line of research that understands misconceptions as novice knowledge that is actually useful in constructing expert knowledge [8]–[10]. Whether one considers misconceptions to be an incorrect set of concepts that needs to change or to be a set of transitional knowledge that will evolve into accepted scientific knowledge, instruction is a crucial part of it. Identifying and correcting misconceptions has been studied for decades both in the sciences and engineering.

An important method in identifying students' misconceptions is concept inventories. Concept inventories are tools that generally include multiple choice questions which include the correct concept and a variety of misconceptions associated with the concept. Page Keeley started to develop concept inventories, which she calls assessment probes (APs) and formative assessment classroom techniques, in 1992 due to an interest in how instruction could change students' concepts [11]. Her APs are primarily designed to be used on K-12 education, although many college instructors use them.

This study uses two of Keeley's APs to identify the misconceptions that civil and environmental engineering students participating in a sophomore-level required course may have. The tested concepts are the greenhouse effect and heat transfer. The course, Engineering for Sustainability, focuses on the application of basic math, physics, and chemistry knowledge to engineering problems, which is one of the ABET requirements for accreditation [4]. The course covers sizing of non-renewable and renewable energy systems, as well as design of green infrastructure for stormwater management, and sustainability rating tools. Early in the semester, students receive instruction about the greenhouse effect, a concept that is later used in the discussion of human-led climate change and engineering technologies that could help alleviate some of climate change's impacts. Soon after students discuss climate change, they receive instruction on heat transfer and thermodynamics, concepts that are utilized in heat exchange systems for electricity generation (non-renewable and renewable energy sources design). The aim of this paper is to quantitatively and qualitatively analyze students responses to Keeley's APs to answer two questions: 1) What is the percentage of students that have misconceptions about heat transfer and how do the explanations they provide can shed light into the kind of misconceptions they have?; and 2) What is the percentage of students that have misconceptions about the greenhouse effect and what other concepts are linked with these misconceptions?

Methods

Participants and Context

Students enrolled in the Engineering for Sustainability course were the target of this project. The data generated by students enrolled in the course from Fall 2016 to Fall 2018 was analyzed (total of 299 students). The number of students that answered the APs in different semesters can be seen in Table 1.

Table 1 – Number of students that responded to each AP from Fall 2016 to Fall 2018. The Heat Transfer probe was not used in Spring 2018 while the Greenhouse Effect probe was not used in Fall 2016 semester.

	Fall 2018	Spring 2018	Fall 2017	Spring 2017	Fall 2016
Heat Transfer	55	N/A	51	65	62

Greenhouse Effect	59	59	51	68	N/A

Assessment Probes

Assessment probes are an important part of this semester-long course. A variety of APs are used during the semester and the two APs discussed here have been developed, designed, and published by Keeley [5], [6]. In the course, APs are worth a very small amount of points each (low-stakes assessments) and serve three purposes: 1) incentivize students to engage with required online material before attending class, 2) help students become aware of any misconceptions they may have developed in previous years, and 3) help the instructor identify and correct any misconceptions students bring to the course before new content is introduced. Both APs studied here are administered in class early in the semester. The Heat Transfer probe is called Ice-cold Lemonade [6]. This AP describes a situation in which a person adds ice to a warm glass of lemonade. After some time, the ice melts and the lemonade is colder. The AP prompts students to choose the best explanation to the phenomenon out of three options: 1) "The coldness from the ice moved into the lemonade," 2) "the heat from the lemonade moved into the ice," and 3) "the coldness and the heat moved back and forth until the lemonade cooled off." After choosing the best description of the phenomenon, students provide an explanation.

The Greenhouse Effect probe [5] (Figure 1) provides 14 statements and prompts students to mark the statements that apply to the greenhouse effect. Later, students must explain what they understand by the greenhouse effect.

Many people have heard of "the greenhouse effect." But what does that mean? Put an X next to the statements you think apply to the greenhouse effect.

____ **A.** The greenhouse effect is related to increasing global temperatures.

____ **B.** The greenhouse effect supports why we should stop building greenhouses.

____ **C.** The greenhouse effect is about the thinning of the ozone layer.

____ **D.** The greenhouse effect contributes to increased incidences of skin cancer.

____ **E.** The greenhouse effect reduces the amount of oxygen in the atmosphere.

____ **F.** The greenhouse effect is caused by using spray cans and air conditioners.

____ **G.** The greenhouse effect is the same thing as global warming.

____ **H.** The greenhouse effect is the main cause of hurricanes.

____ **I.** The greenhouse effect can contribute to a change in weather patterns.

____ **J.** The greenhouse effect can be reduced by using unleaded gasoline.

____ **K.** The greenhouse effect is related to increased use of fossil fuels.

____ **L.** The greenhouse effect is one of the causes of acid rain.

____ **M.** The greenhouse effect is related to human activities.

____ **N.** The greenhouse effect can be controlled by keeping beaches clean.

Explain your thinking. Describe what you know about the greenhouse effect.

Figure 1 – Cutout of Keeley's The Greenhouse Effect assessment probe [5].

Analysis

The frequencies of misconceptions about the two underlying concepts tested by the APs were calculated. Moreover, a qualitative analysis of the students' explanations was conducted to establish the possible root-cause of these misconceptions.

Findings and Discussion

Question 1 - What is the percentage of students that have misconceptions about heat transfer and how do the explanations they provide can shed light into the kind of misconceptions they have?

Aside from being instructed on the concepts of heat and energy transfer during K-12 education, students enrolled in Engineering for Sustainability must first successfully complete General Chemistry for Engineers, a basic chemistry course that includes energy transfer concepts. Moreover, at this point, students most likely already have successfully completed a basic physics course as well, which tends to include instruction on different types of energy. Before students come to class and the AP is used, they are required to access and interact with online content. In the case of this lecture, the required online content includes the laws of thermodynamics and two videos where energy is discussed. The required online content alone should suffice for the successful completion of this AP. However, one cannot assume that 100% of the students complete the required content before attending class. Moreover, ideas about energy, heat, cold, and how energy transfer occurs may already be part of the students' constructed idea of the natural world and the material may not be enough to break from these previously constructed ideas.

The heat transfer AP offers students three possible explanations for why ice melts when in contact with warm lemonade: 1) "The coldness from the ice moved into the lemonade," 2) "the heat from the lemonade moved into the ice," and 3) "the coldness and the heat moved back and forth until the lemonade cooled off." Most of the students choose the correct explanation, which is option 2. In Fall 2018, 61.8 % (n = 55) of the students chose this option, while in Fall 2017, Spring 2017, and Fall 2016 82.4 % (n = 51), 87.7 % (n = 65), and 80.6 % (n = 62) of the students opted for the second explanation respectively (Table 2). The data suggests that, in the last semester of analysis (Fall 2018), a larger number of students chose the incorrect option. It is difficult to predict if this will become a trend in the next semesters.

Table 2 – Number of students and their respective answers to the Heat Transfer AP.

	Fall 2018	Fall 2017	Spring 2017	Fall 2016
Option 1	2	1	3	3
Option 2	34	42	57	50
Option 3	19	8	5	9
Total	55	51	65	62

Engineering students' misconceptions in thermodynamics and particularly in heat and energy have been studied before [7], [12]–[16]. Foroushani [7] noted that the least understood concept in thermodynamics is heat transfer, and that students tend to understand heat as an entity and not as a process. Keeley herself noted this during her research of the original concept inventory tool used here [6] and included suggestions of how instructors could address the misconceptions in the post-AP discussion. Nottis et al., [15] in their study with chemical engineering undergraduates, concluded that new instructional methods should be developed to address misconceptions about heat transfer and suggested that inquiry-based activities could be key to address these hard-to-grasp concepts.

Along with understanding heat as an entity, some students may also understand that cold moves. These ideas generate both incorrect responses in the AP used and they were used in students' explanations. For example, one student wrote: "... the coldness from the ice in the lemonade caused the lemonade to cool down, but the heat of the lemonade caused the ice to melt and release energy to the lemonade." This statement demonstrates that the student understands coldness and heat as entities that move from one object to another, which is a common misconception. This kind of statement was common in the responses from students that choose the incorrect options. It is possible that these misconceptions are constructed early on by exposure to this type of language during K-12 education, but it is also likely that they are socially-constructed.

Addressing these misconceptions has life-long implications. It is quite likely that many of the students taking this course will not work directly with concepts of thermodynamics in their professional lives. However, understanding these concepts is quite important for a variety of engineering applications. For example, thermodynamics and heat transfer are essential knowledge to design an energy-efficient building. Within the course, these concepts are later applied to non-renewable and renewable energy generation design (cooling systems for example). These concepts are also used in problems that cover how heat can be used to produce electricity and to generate a phase change in water or another substance. The use of the AP in the class allows the instructor to address the misconceptions immediately after students conclude the AP. A follow-up discussion is conducted using think-pair-share and large group techniques. The discussion aims to address these misconceptions with the intention that students incorporate the scientifically-accepted view of these concepts in their own body of knowledge.

Question 2 - What is the percentage of students that have misconceptions about the greenhouse effect and what other concepts are linked with these misconceptions?

Before the greenhouse effect AP is used in the class, students are required to engage with online material. Among other materials, students watch a 3-minute video on how greenhouse gases work and what the greenhouse effect is. As previously mentioned, one cannot assume that all students engage with the material before coming to class. The greenhouse effect AP contains 14 statements (A-N) and prompts students to choose the statements that apply to the greenhouse effect [5] (Figure 1). The statements that apply to the greenhouse effect are: A) The greenhouse effect is related to increasing global temperatures, I) The greenhouse effect can contribute to a change in weather patterns, K) The greenhouse effect is related to increased use of fossil fuels, and M) The greenhouse effect is related to human activities. These statements are quite broad and in general students understand them to be true. In fact, the vast majority of the students marked these statements in the AP (Table 3). On average, throughout all four semesters analyzed, more than 92% of the students mark these statements, which shows that students do have a general understanding of the greenhouse effect. However, the number of students that choose these options and no other option (perfect score on the AP) is small. In Spring 2017, only 4.4 % of students had a perfect score on the AP, in Fall 2017 the number was 2.2 %, in Spring 2018 it was 5.1 %, and in the Fall 2018, the number went up to 20.3 %. Perhaps the reason why such a small number of students get a perfect score on this AP is that the statements provided by the AP are broad and some may be misunderstood.

Table 3 – Percentage of students that marked statements as related to the greenhouse effect. Correct statements are indicated with an asterisk.

Statement	Fall 2018 (n = 59)	Spring 2018 (n = 59)	Fall 2017 (n = 51)	Spring 2017 (n = 68)	Average (n = 237)
A*	96.6	98.3	92.2	100.0	96.8
B	0.0	0.0	0.0	1.5	0.4

C	47.5	52.5	45.1	54.4	49.9
D	23.7	44.1	45.1	50.0	40.7
E	28.8	27.1	27.5	26.5	27.5
F	11.9	32.2	35.3	48.5	32.0
G	28.8	20.3	29.4	25.0	25.9
H	3.4	8.5	7.8	7.4	6.8
I*	96.6	89.8	92.2	97.1	93.9
J	15.3	11.9	9.8	11.8	12.2
K*	94.9	88.1	90.2	95.6	92.2
L	40.7	47.5	51.0	48.5	46.9
M*	94.9	88.1	98.0	97.1	94.5
N	3.4	3.4	7.8	2.9	4.4

The four least popular statements (on average less than 12.2 % of the students mark these statements) are B) The greenhouse effect supports why we should stop building greenhouses, H) The greenhouse effect is the main cause of hurricanes, J) The greenhouse effect can be reduced by using unleaded gasoline, and N) The greenhouse effect can be controlled by keeping beaches clean. These four statements are not linked to any specific misconception surrounding the greenhouse effect, so we should expect they will only receive a small portion of marks. In her original research for the design of this AP, Keeley found that younger students sometimes conflate environmental issues together and some students get confused about the literal definition of a greenhouse when compared to the greenhouse effect [5], [17], [18]. This may become much less important with time, and by the time students get to post-secondary education, some of these misconceptions may not exist anymore. However, not all misconceptions about the greenhouse effect disappear as the data in Table 3 suggests.

One major misconception that is present among the students that participated in this project is that that the greenhouse effect is one of the causes of acid rain. On average, throughout all the semesters analyzed here, 46.9 % of the students marked option L) The greenhouse effect is one of the causes of acid rain. The root of this misconception may be simply the fact that students tend to conflate environmental issues (as suggested by Keeley) and these two environmental phenomena (greenhouse effect and acid rain) occur in the atmosphere. It is noteworthy though that almost half of the student population investigated in this study (sophomores and juniors in a major research school) still cannot correctly assess that the greenhouse effect does not cause acid rain.

The most prevalent misconception in this study was rooted in the mixing up of greenhouse effect with holes in the ozone layer. Keeley herself knew about this possible issue and therefore the AP contains three statements that aim at identifying this misconception: C) The greenhouse effect is about the thinning of the ozone layer, D) The greenhouse effect contributes to increased incidences of skin cancer, and F) The greenhouse effect is caused by using spray cans and air conditioners. On average, throughout all the semesters analyzed here, 49.9 % of students marked option C, 40.7 % of students marked option D, and 32.0 % marked option F. Statement C suggests a direct relationship between the thinning of the ozone layer and the greenhouse effect, while statements D and F suggest indirect relationships between the two concepts. This result is not surprising. Other researchers have investigated this misconception in students of different ages and it seems that this misconception is common in students living in several parts of the world [17], [19]–[25]. Libarkin et al. [21] produced research with college students and analyzed conceptual models of students constructs of the greenhouse effect based on student drawings. In their work, they suggest that research tools that cannot separate students reasoning may be obscuring the sources and details of the students' misconceptions. This may be the case with Keeley's AP. The written answers provided by the students may be able to shed light into some of the reasoning behind their choices and misconceptions. For example, one student wrote: "Greenhouse effect shows how earths[sic] atmosphere entraps CO2[sic] and how we have issues in trying to release the excess amounts we produce thus leading our ozone to slowly diminish." This student's explanation is common to students that marked one, two, or all three options linked to the ozone layer misconception. It is important to note that this and other students write about disconnected pieces of information and try to link them to provide an explanation, which is also noted in another study with college students [21].

This AP provides ample information about several student misconceptions and provides the opportunity to discuss them in class before new content that depends on this concept is introduced. According to this and other research on the topic, it is clear that these misconceptions need to be addressed throughout a student's education including well into college education.

Conclusions and Future Work

This study utilized two assessment probes to identify students' misconceptions regarding greenhouse effect and heat transfer. The student population that participated in the study was enrolled in a required course for civil and environmental engineering students at the sophomore-level. In general, analysis of the data shows that between 12.3 and 38.2 % of the student population has misconceptions with regards to heat transfer concepts. These misconceptions are rooted in their ideas of heat and cold as entities that move between objects. With regards to the greenhouse effect, more than 95 % of the students showed a variety of misconceptions. The most prevalent misconception associated with the greenhouse effect is conflating it or closely relating it to the thinning of the ozone layer. Future research will determine if classroom instruction conducted after the APs were utilized and discussed was able to correct these misconceptions. AP data will be linked with specific exam questions that test these concepts and also with overall course grade to analyze if students that bring misconceptions to the course are at a disadvantage in terms of overall course performance.

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