

Reframing Analogy: framing as a mechanism of analogy use

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Abstract. In a series of large-scale ($N > 100$) studies of analogy use in college physics, we have explored how, when, and why analogies affect student reasoning. In the first of these studies, we demonstrated that analogies affect student reasoning when taught in a large enrollment physics course [1]. In the present follow-up study, we demonstrate that teaching EM waves concepts implicitly via analogy leads to greater conceptual change compared to teaching explicitly without analogies. Students were divided into two groups, one taught using analogies (string and sound waves) and the other taught without analogies (EM waves only). On a targeted concept question given before and after instruction, students who were taught with analogies outperformed those taught without analogies demonstrating that analogies can affect student reasoning in productive ways, even when taught implicitly. We propose framing as a mechanism to begin to explain why analogies can be productive when used implicitly.

Keywords: analogy, framing, electromagnetism, waves

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INTRODUCTION

Analogies are commonly used by both physics teachers and by practicing physicists. The purpose of an analogy is to ground an unfamiliar concept in terms of a more familiar one. An often cited example is the planetary model of the atom. While the original utility of this analogy was for physicists to explain the results of experiment [2], it is also used to teach an introductory, albeit incomplete, model of the atom to students. An analogy can be defined as a mapping from a base domain (e.g., the solar system) to a target domain (e.g., the atom), akin to a mathematical isomorphism. [3] In the planetary model of the atom, the sun maps to the nucleus, planets to electrons, the gravitational force to the Coulomb force, etc.

The ubiquity of analogies in physics textbooks [4,5] as well as the findings of some researchers (e.g. [6]) suggest teaching with analogies can sometimes be a productive instructional strategy. It has been demonstrated that analogies amount to more than colorful language [7]. In fact, they can generate inferences, shaping learners' conceptions of a target domain. In the example above, the solar system analogy generates the inference that electrons in an atom are tiny spheres that revolve around the nucleus. Some researchers, however, have found that teaching with analogies is only sometimes productive. [8,9] Thus, analogies do generate inferences, but only under certain conditions. These researchers hypothesize that

teaching with analogies can fail to change students' conceptions for a number of reasons, including: 1) students may have an inadequate understanding of the base domain to map; 2) the base domain or the relationship between base and target may be too abstract; 3) students may not know how to make productive mappings [8,9].

These hypotheses have led to a common view that effective teaching with analogies should include explicit instruction as to which mappings are productive for understanding the target domain, and which mappings may be harmful [5]. In the present study, we took a different, but more common, approach and taught analogies implicitly. That is, we explicitly taught students the base domains to learn about a target, but did not explicitly instruct students on which mappings to make.

To date studies of analogy in physics have only demonstrated success when taught to small numbers of students ($N < 20$) with a focus on explicit instruction (e.g., [8,9]). We build on this previous research on analogy in a series of studies, including large-scale ($N > 100$) studies and student interviews, to ask whether and how analogies might be productively taught in the canonical large enrollment physics courses. These studies focus on student learning of electromagnetic (EM) waves, a topic with which students have difficulty [10].

Two analogies commonly used to teach EM waves are a wave on a string and sound waves. In our first large-scale study, we taught students about EM waves

using either a wave on a string or a sound wave as an analogy [1]. We tested the effectiveness of the analogies using concept questions given after instruction. We found that the analogies did affect student reasoning. For instance, on a multiple choice concept question similar to Figure 1, we found that students' answers were associated with which analogy they were taught (string or sound). The distracters students chose reflected characteristics of the particular analogy they were taught. For instance, students who were taught a string analogy tended to choose a distracter that characterized an EM wave as two dimensional, which is characteristic of an oscillating string. Thus, different analogies generated correspondingly different inferences about EM waves. In fact, EM waves have characteristics of both waves on a string and sound waves.

In interviews, we found that students had difficulty answering the same EM wave concept question when taught only about EM waves. Suggesting string and sound wave analogies verbally to students did not substantially help these students in answering the concept question. However, we found that providing iconographic string and sound wave representations as analogies to EM wave representations did help students make significant progress towards answering the concept question correctly.

Based on these prior findings, we hypothesize that the optimal approach to teaching EM waves would be to use both string and sound analogies. In the present study, we taught students about EM waves using both string and sound analogies, or without analogies. We compared the effectiveness of these two teaching methods with a concept question targeted specifically to the concepts in the tutorial, and with follow-up interviews. Here, we focus on results from the concept question. We found that students who were taught EM wave concepts implicitly via analogy performed better than students who were taught the same EM wave concepts explicitly but without analogies. Thus, we confirmed our earlier findings that analogies generate inferences when taught in a large scale physics course. Further, we demonstrated that the findings of small scale studies (i.e. that analogies generate inferences) are reproducible in a large-scale study.

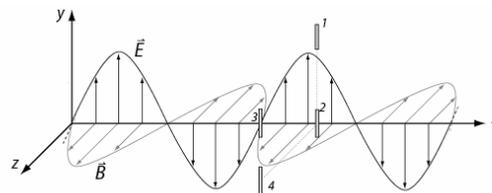
EXPERIMENTAL METHODS

The experiment involved $N=156$ students enrolled in a second semester, calculus-based physics course at a large university. The course consisted of three lectures and a single 50-minute recitation each week. The lectures made extensive use of clickers and concept questions, but were otherwise traditional (as described in [11]). Recitations were led by two or

three teaching assistants, where students used the *Tutorials in Introductory Physics* [12].

For the present experiment, students were divided into two groups, denoted the analogy ($N=72$) and no-analogy ($N=74$) groups. In both groups, students completed a modified tutorial on EM waves that borrowed heavily from the *Tutorials*. The tutorial consisted of three sections. Section 1 covered basic wave concepts such as wavelength, frequency, and amplitude as well as traveling vs. standing waves. Section 2 covered plane wave concepts, focusing on the idea that they are three dimensional (3D) waves. Section 3 covered EM wave representations and forces on charges due to the electric and magnetic fields of an EM wave. For students in the analogy group, section 1 focused on a wave on a string, and section 2 grounded the study of waves in sound waves. The only section of the analogy tutorial that discussed EM waves was section 3. The no-analogy tutorial was very similar in length and content to the analogy tutorial, and used sections nearly isomorphic to the analogy tutorial to teach these concepts, but always in the context of EM waves. Notably, only approximately 1/3 of the analogy tutorial dealt explicitly with EM waves, while the entire no-analogy tutorial was dedicated to EM waves. Teaching assistants were told not to use analogies when teaching in the no-analogy sections, but were encouraged to use analogies when teaching in the analogy sections.

To compare the effectiveness of the analogy and no-analogy tutorials, a challenging concept question on EM waves was given in lecture on the days immediately prior to and after recitation. Students were asked the concept question shown in Figure 1. Since students from both groups attended the same lecture, students were told not to discuss the question with their in-class peers until after the entire class had finished responding. Individual student responses were collected electronically and only students who attended the recitation and responded to the questions both before and after and were included in the study.



An electromagnetic plane wave propagates to the right in the figure above. Four antennas are labeled 1-4. The antennas are oriented vertically. Antennas 1, 2, and 3 lie in the x - y plane. Antennas 1, 2, and 4 have the same x -coordinate, but antenna 4 is located further out in the z -direction.

Which choice below is the best ranking of the *time-averaged signals* received by each antenna? (*Hint: the time-averaged signal is the signal averaged over several cycles of the wave.*)

- A) $1=2=3>4$ B) $3>2>1=4$ C) $1=2=4>3$ D) $1=2=3=4$ E) $3>1=2=4$

FIGURE 1. Multiple choice EM wave concept question.

RESULTS

The results for the EM waves concept question are shown in Figure 2. The vertical axis shows the gain, or difference in responses between the concept question given before (pre) and after (post) recitation for the analogy and no-analogy groups. The two answers with positive gain were the correct answer ($1=2=3=4$) and main distracter ($1=2=4>3$). In both groups, more than 86% of students chose one of these two answers on the post-test. We found that the gain on answering with $1=2=4>3$ was 24% in the analogy group and 38% in the no-analogy group. The gain on answering with $1=2=3=4$ was 21% in the analogy group and 7% in the no-analogy group. Thus, the analogy group had a greater gain on the correct answer, and the no-analogy group had a greater gain on the main distracter ($p<0.1$, 1-tailed z-test).

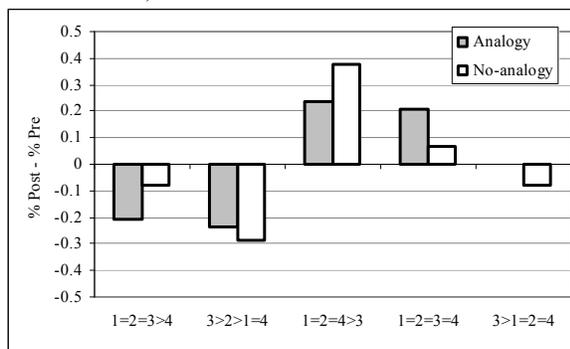


FIGURE 2. Results on the EM wave concept question. Vertical axis is the gain (% Post - % Pre) for the analogy and no-analogy groups. Multiple choice answers are shown below the horizontal axis. Gain on $3>1=2=4$ for the analogy group was zero.

DISCUSSION

Interpretation of Results: Based on the above results, we point out two key findings: 1) Students changed their conceptions of EM waves whether taught with or without analogies, and 2) The students in the analogy group made greater progress towards the correct answer compared to students in the no-analogy group. These findings demonstrate that analogies, taught implicitly, successfully generated inferences about EM waves.

The concept question above requires students to understand at least two characteristics of EM waves. First, EM waves are plane waves. Thus the time averaged signal is equal at antennas 1, 2, and 4. Second, this particular EM wave is a traveling wave, so the time-averaged signal at antenna 3 is the same as that at 1, 2, and 4. In the no-analogy tutorial, these ideas were all addressed explicitly for EM waves. Thus, students in the no-analogy group were taught

explicitly that EM waves can be traveling waves and that they are plane waves. In the analogy tutorial, these ideas were taught for analogous situations, but not EM waves. Students learned that waves on a string can be traveling waves, and that sound waves are (locally) plane waves. In order to answer the EM waves concept question correctly, students in the analogy groups had to apply their knowledge of string and sound waves to EM waves.

We find more specific details in our results as well. Note that both the correct answer and the main distracter include the characteristic $1=2=4$. We will refer to this characteristic as the plane-wave feature. The additional feature in the correct answer is the traveling-wave feature (i.e. 3 is equal to the others). What we have found is that most students chose an answer that contained the plane-wave feature – in both groups, the gain on the correct answer and main distracter combined was 45%, and more than 86% of students chose one of these answers on the post-test. Thus, this feature maps strongly from sound waves to EM waves since, in the analogy group, it was never taught explicitly for EM waves. The traveling-wave feature appears to be more difficult to teach, either by analogy or directly. There may be several reasons for this difficulty, one of which is the appealing idea for students that antenna 3 lies at a node. Teaching with analogies seems to have marginally better success at overcoming this difficulty.

What we found is that the analogies affected student reasoning about EM waves when taught implicitly. It is possible that teaching the analogies explicitly may have resulted in a more pronounced effect. However, implicit teaching of analogies is a common practice, and our findings suggest that these practices can affect student reasoning.

A Mechanism of Analogy: The fact that we did not instruct students explicitly on how to use the analogies leads us to ask how students knew to reason about EM waves (i.e., make mappings) as they did. We believe that existing theories of analogy (e.g. [8]), while essential for creating productive analogies, do not explain the way people commonly use analogies implicitly. To begin to explain this, we posit a complementary view of analogy. According to this view, analogies work because the base domain provides a frame, or conceptual structure, which can be applied to the target domain. A frame exists as a compiled set of ideas that can be cued, or activated, together [13,14]. In the analogy tutorials, we used several iconographic representations to teach string and sound waves. In each case, students were taught that a sine wave could be used to represent each type of wave. By using the sine wave in different contexts, students may have compiled more and more meaning into that particular wave representation [15]. Thus, the

sine wave frame consists of generic features of waves, such as traveling and 3D. When the same sine wave representation was then used to reference the EM wave, the existing sine wave frame was cued, and could be applied to the unfamiliar target domain of EM waves. The result is that content specific to EM waves, such as the electric field, takes on the structure of the frame, producing a model of electric field propagating as 3D waves. One reason this approach may work, in spite of being taught implicitly, is that creating and cueing frames is largely an unconscious, but extremely powerful, cognitive process. Such unconscious processes may require less cognitive work from students than conscious processes [14].

While we found analogies led students to greater progress towards the correct answer on the concept question, these ideas remain difficult for students to master, and the effect of using analogies is not so pronounced. We offer two hypotheses as to why this might be. One is time on task. Although we found that a single 50-minute recitation was sufficient to change some student conceptions of EM waves, it might not have been sufficient to promote learning of more difficult concepts. Further, students in the analogy group spent less time learning EM waves specifically compared to the no-analogy group. Given more time with EM waves, students prepared with analogies may have performed substantially better.

A second hypothesis we will propose recognizes the distinction between everyday and classroom knowledge [16]. In student interviews conducted as part of this study, we have observed that students are not always able to apply everyday knowledge of string or sound waves, but are able to apply classroom knowledge (i.e. drawn from particular wave representations) to learn about EM waves. For instance, we observe that when presented with a sine wave representation of sound, some students state that the sound can only be heard in the plane of the sine wave. The usefulness of analogies rests on the assumption that students will ground their understanding of unfamiliar ideas in terms of the familiar. The tutorials used in this study were designed to draw on students' familiar, everyday knowledge, and couple this to abstract classroom knowledge. However, in the context of a physics course, students may not use the resources that analogies are meant to draw on. That is, even though students have had everyday experiences with waves on a string, they may not bring this knowledge to bear in a classroom setting. Both the analogies and formal representations may be treated as equally abstract by students. This hypothesis suggests future studies on whether and how students use everyday knowledge when reasoning by analogy in a classroom setting.

CONCLUSION

In a large scale study of student use of analogy, we have demonstrated that analogies generate inferences when taught. We found that teaching EM waves implicitly via analogy led to better student performance than teaching explicitly without analogies. Student reasoning about EM waves was affected when taught with both methods, but we found students who were taught with analogies made better progress towards the correct answer on a pre-post concept question. We have begun to explore how teaching of analogy can work, and posit that the underlying mechanism may be the creation and cueing of cognitive frames and use of representations.

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