2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #39970

Metaphor: The Key to Communicating with Both Specialists and the Public

Amanda Dawn Hilliard, The Johns Hopkins University

Amanda Hilliard received her MA in Teaching English as a Second or Foreign Language and PhD in Applied Linguistics from the University of Birmingham in the UK. She has taught writing and communication courses abroad in South Korea, Vietnam, and Ecuador, and in the U.S. in Georgia, Texas, Arizona, and Maryland. She currently teaches in the Center for Leadership Education at the Johns Hopkins University.

Metaphor: The Key to Communicating with Both Specialists and the Public

While metaphor is vital to the development and spread of scientific knowledge, engineers may overlook the critical role of metaphor in communicating their research to both specialist and non-specialist audiences. Therefore, this study investigated how graduate-level engineering students employed metaphor in both academic journal articles and scientific magazine articles. In a writing and communication course, 14 graduate-level engineering students read an article about metaphor in science, received a lesson on conceptual metaphor theory, and analyzed metaphor in articles from *The Best Science and Nature Writing*. Finally, the students wrote both an academic article for a specific journal in their fields and a scientific magazine article for a wider audience, which were then analyzed for metaphor frequency, conceptual metaphor, conventional metaphor, creative metaphor, personification, metaphor signaling, extended metaphor, and visual metaphor. Overall, students used a similar amount of metaphor in both articles, but seemed to appeal to different audiences by employing more conventional metaphor and visual metaphor in the journal articles and more extended and creative metaphor in the magazine articles. Although metaphor is only one of many tools to explain complex scientific concepts, the findings suggest engineering students may appreciate metaphor more if we point out how metaphors are used in fixed expressions in scientific fields, how metaphors help scientists process abstract information, or how metaphors can translate scientific research for the public. Moreover, this study emphasizes the need for writing and communication classes that target multiple audiences as an integral part of any graduate-level engineering curriculum.

1. Introduction

In the groundbreaking 1980 book *Metaphors We Live By*, Lakoff and Johnson explain that rather than simply serving as a poetic device, metaphor structures "how we perceive, how we think, and what we do" every day [1, p. 4]. In the decades since their book was first published, cognitive linguists have researched how we express conceptual metaphors linguistically [2]-[5], proposed different mechanisms for how we mentally process metaphors [6], [7], and offered competing cognitive models to Lakoff and Johnson's Conceptual Metaphor Theory [8]. While rigorous academic debate continues in this area, it is clear that metaphor is more than just a linguistic phenomenon. In short, our conceptual system is metaphorical, and this naturally extends to the way we perceive, understand, and test ideas in science. In fact, we use our everyday experiences to draw metaphorical comparisons that help us create new theories, explain concepts, and communicate abstract scientific ideas.

Despite this, many scientists overlook the role metaphor plays in how they conceptualize and discuss scientific ideas, so metaphor is rarely a focus in graduate-level engineering education. But if metaphor is pervasive in language and thought, then it is also vital to scientific communication. Therefore, this study incorporated an explicit focus on metaphor into a graduate-level engineering writing course and analyzed the students' metaphor use in both an academic journal article and a scientific magazine article. The findings show that metaphor is a common feature of both students' academic journal articles and scientific magazine articles, but the type and purpose of metaphor differs depending on the intended audience.

1.1 Conceptual Metaphor

According to Lakoff and Johnson's framework, we use more concrete, familiar areas from our everyday experiences (source domains) to understand more abstract concepts (target domains) [1]. The source and target domains can be written as an overarching conceptual metaphor that represents a systematic way of thinking. For example, in the conceptual metaphor TIME IS MONEY, we use our everyday experiences with money to help us conceptualize the more abstract domain of time. This conceptual metaphor can then be expressed linguistically in different ways, for example "You're *wasting* my time," and "This gadget will *save* you hours." Lakoff and Johnson [1] also point out that different cultures may conceptualize time differently or may linguistically express the same conceptual metaphor using different wording.

In the book *Making Truth: Metaphor in Science*, Brown [9] similarly explains that we understand nature and science based on how we interact with the physical world around us. Therefore, our concrete, physical interactions (source domains) help us understand abstract scientific concepts (target domains). Brown [9] includes examples of conceptual metaphors for understanding atoms, protein folding, and global warming to show how scientists from different disciplines understand their fields in terms of metaphorical concepts. Thus, scientific reasoning, models, and theories all rely on conceptual metaphor.

1.2 Conventionality of Metaphor

Metaphor can be classified by conventionality, or "how deeply entrenched a metaphor is in everyday use by ordinary people for everyday purposes" [5, p. 33]. At one end of the continuum, "dead" metaphors, also called frozen or historical metaphors, are so familiar that they may no longer evoke their original metaphorical imagery or meaning. For example, when we use "cell" in biomedical engineering or "virus" in computer science, we probably do not think of their original metaphorical meanings. However, some researchers prefer the terms "sleeping" or "waking" metaphor since "as long as metaphoric expressions are transparent, metaphoricity can be vitalized" and foregrounded [10, p. 297]. For example, when comparing metaphor in research articles, textbooks, and student interviews, [11] found that the term "greenhouse" appeared as a purely technical term for experts but that textbooks encouraged students to consider its figurative meaning, which often appeared in students' explanations of the greenhouse effect. In other words, while the metaphoricity of the term "greenhouse" was dead to the researchers, it was used as a pedagogical tool in the textbooks and was very salient for the students. At the other end of the continuum are creative metaphors. Also known as novel metaphor or unconventional metaphor, this is an original comparison between two unrelated domains (as opposed to conceptual metaphor discussed above). When people typically think of metaphor, examples of creative metaphor from poetry and literary works often spring to mind.

Regardless of conventionality, writers may use metaphor signaling to make a metaphorical meaning more salient for the reader. For example, terms such as "like," "as if," or even the word "metaphor" itself can flag an upcoming figurative usage for the audience. Along with these metaphor signals, both conventional and creative metaphors can appear in isolation or can be used repeatedly throughout a passage. A metaphor that is developed over the course of multiple sentences or paragraphs is referred to as extended metaphor and can help structure a longer passage. More recent research has also highlighted how both conventional and creative metaphor can appear not only linguistically, but also in visuals [12], [13].

1.3 Metaphor in Science

Metaphors are vital to scientific reasoning [14]-[18]. Reeves [14] explains that metaphors are inescapable in science as human beings must draw from various domains of experience to make sense of new domains they encounter. In other words, metaphor facilitates scientific thinking by helping scientists create new concepts, hypotheses, models, and theories to explore in their research [14], [15]. Metaphor also serves a cognitive function and enables analogical reasoning that can help scientists understand the world around them [15]. Ultimately, metaphor is a tool that helps scientists mold and manipulate the objects they study [15].

Metaphors also help us communicate about science, both between scientists and with non-scientists [14], [15]. For example, Deignan and Semino [19] compare a research article on megafauna from the journal *Science* with its translated version for the general-audience magazine *New Scientist*. The original *Science* article uses visual metaphor to represent data in a graph and describes the data visualization using metaphorical terms such as "saw-tooth pattern," "tie-points," "curve," and "falling." In contrast, the popular science article omits the graph but employs a more creative, extended trial metaphor for different possible explanations of megafauna extinctions, adding drama and humor to attract and entertain a general audience. Even when texts employ the same metaphor, they use metaphor differently to communicate with different audiences. [19] found that the term "greenhouse" has a purely technical meaning for scientists in formal research papers but appears in similes and expanded explanations in textbooks and websites. Similarly, [20] highlights uses of COVID-19 AS A WAR metaphors in the journal *Nature*, the magazine *New Scientist*, and the World Health Organization website. While the war metaphor serves an explanatory function in all three sources, it also offers different viewpoints depending on the targeted readers, editorial requirements, and aims of the publication.

Despite the importance of metaphor in scientific thinking, research, and communication, some scientists may avoid using metaphor and analogies for fear they are too subjective and could lead to misunderstanding and misconceptions [21]-[23]. Metaphor allows us to use our embodied, everyday experiences to understand more abstract, intangible phenomenon, so metaphor will highlight some aspects of the target concept while hiding others [1]. For example, Taylor and Dewsbury [21] point out that the metaphor of genes as blueprints highlights how genes shape our development but is oversimplistic and incompatible with recent developments in genetic research. Some have proposed a gene as a recipe metaphor to incorporate the role of the environment in gene expression, but this metaphor also has its drawbacks. Moreover, conventional metaphors in science may have unintended sociopolitical messages or alienate certain individuals or groups. For example, the metaphors surrounding "invasive species" may incite fear even though scientists debate what constitutes a native vs. an invasive species, and the use of racially loaded metaphors like "slave-making ants" could be offensive [21].

While there is no perfect one-to-one comparison, Taylor and Dewsbury [21, p.5] note that "metaphors are indispensable tools for both practicing and communicating science." So, rather than avoid metaphor altogether, we should carefully develop good analogies and metaphors while remembering their possible limitations, unintended sociopolitical messages, and potential for misunderstanding [21], [22]. Indeed, students often misunderstand instructional analogies and metaphors or fail to use them in their own explanations of scientific phenomenon [11], [24]. After reviewing previous science education research, Niebert, Marsch, and Treagust [24] conclude that effective instructional analogies and metaphors must go beyond just making a connection to everyday life; rather, they must come from embodied sources and scenarios familiar to the students. For example, research on science classes showed that an elaborate analogy of a school dance with blindfolded participants and restricted space was less effective at teaching the concept of equilibrium than the more relatable metaphor of dissolving sugar in a teacup [25].

To sum up, metaphor structures how we think on a conceptual level [1], so it is an important part of scientific reasoning, communication, and instruction [14]-[18]. Metaphors vary greatly and may be more conventional or more creative, may include signaling or not, may appear only once or be repeated throughout a passage, and may appear linguistically or in visuals. Considering this variety, writers adjust their metaphors to suit the purpose, level, and expectations of various audiences [19], [20]. With this background in mind, this study analyzed how graduate-level engineering students used metaphor to write for both a specialist and a non-specialist audience. The main research questions were:

1. How do students use metaphor in their journal articles and in their scientific magazine articles?
2. What are the similarities and differences in metaphor use across the two genres?

2. Methodology

2.1 Participants

The 14 students in this study were taking an interdisciplinary, semester-long, graduate-level writing and communication course in an engineering school. The most common major was Chemical and Biomolecular Engineering (8 students) followed by Mechanical Engineering (2 students). The remaining four students were studying Earth and Planetary Science, Physics, Computer Science, and Material Science and Engineering. Among the 14 students, ten students were pursuing a PhD, three were enrolled in a MA-level program, and one was an undergraduate student in an accelerated 4+1 BA/MA program. The majority of the students (10 students) were non-native English speakers, while the remaining four students were native English speakers. The students were comprised of 5 men and 9 women. After the course, students were emailed to get permission to feature examples and excerpts from their articles in this paper.

2.2 Course

During the semester-long course, students first read the article "On the Problem and Promise of Metaphor Use in Science and Science Communication" and responded to the following questions in a class discussion board:

1. Name at least 2-3 common metaphors used in your field. What two things are being compared in these metaphors?
2. How can using these metaphors be beneficial and/or misleading for your audience?

In the next class, students discussed benefits and drawbacks of using metaphors in scientific communication. Students were then introduced to conceptual metaphor theory using examples from the article. Finally, students were asked to brainstorm three possible metaphors to use for their own research and discuss them with a partner.

In addition, throughout the semester, students chose articles from *The Best Science and Nature Writing* for their classmates to read for homework and then led a discussion in the following class. For the class discussion, students had to apply concepts from the class and include at least 2-3 examples of how their article appeals to a wide audience, often choosing examples of metaphor from the texts.

Finally, students wrote multiple drafts of two articles during the semester – an academic journal article on their own research and a scientific magazine article translating that research to a wider audience. Students chose the specific journal and magazine they wanted to write for, completing an "audience analysis" assignment for each publication early in the semester. In addition to the audience analysis, the instructions for the course assignments specifically focused on writing for a more technical audience in the journal article and a more general audience in the magazine article. Students received both peer and instructor feedback on each draft and submitted their final articles at the end of the semester.

2.3 Analysis

To analyze the students' metaphor use, linguistic metaphor in each paper was first identified using the Metaphor Identification Procedure VU University Amsterdam (MIPVU) [26],[27]. MIPVU is a systematic process for identifying linguistic metaphors that have the potential to be realized as metaphors in people's minds. Following this procedure, each text is read to get a general understanding of the meaning and lexical units are determined. For each lexical unit, if the contextual meaning of the unit contrasts with the basic meaning of the unit and can be understood in comparison with it, the unit is marked as metaphorical. Once potential linguistic metaphor was marked in each article, the papers were examined for trends in metaphor use across multiple writers in both genres.

3. Results and Discussion

Overall, students used a similar amount but different types of metaphor in the two articles. In the journal articles, students used more conventional and visual metaphor to structure their papers and to accommodate the conventions and expectations of their academic fields. In the scientific magazine articles, students used more creative and extended metaphors as they explained complex concepts. They also used personification and figurative language that evoked emotions and maintained their readers' interest. These results will be discussed in more detail below.

3.1 Metaphor Frequency

The students used a similar amount of metaphor in both types of articles. For the journal article, the average metaphor frequency was 8.4% with a range of 5.2%-12%. For the magazine article, the average metaphor frequency was 9.15% with a range of 6%-11.9%. These results are not surprising as metaphor is prevalent throughout language and many different types of written communication [1]. That said, the slightly lower frequency of metaphor in journal articles could be due to the literal nature of most methodology sections and the lack of creative and extended metaphors in the students' journal articles, as discussed below.

3.2 Conceptual Metaphor

Both the journal articles and magazine articles utilized conceptual metaphors to communicate scientific research. For example, a common conceptual metaphor in the journal articles was KNOWING IS SEEING. Students used phrases such as "as we have seen thus far" to sum up key points in the literature review, "to see how" while providing justification for their methodology, and "we could see that" when interpreting their results and data. Other conceptual metaphors in both types of articles either described a common abstract target domain (e.g. time) or a specific scientific field (e.g. in biomedical research, see [28] for further discussion of conceptual metaphor in science). For example, phrases like "in recent decades," or "in the near future," appeared in both types of articles and linguistically express the conceptual metaphor TIME IS A CONTAINER.

Aside from common phrases or terms in specific fields, students employed different conceptual metaphor in their journal articles than in their magazine articles. In other words, they appeared to choose conceptual metaphors that would translate their research for a more general audience. For example, two students wrote journal articles about research tied to immunotherapies – one about improved vortex trapping for processing immune cells and the other about a method for increasing the lifespan of immunocytokines. The journal articles focused on very technical aspects of the research, so employed personification of the cells and metaphors like the "therapeutic window of treatment" and "family" of cytokines. However, for their scientific magazine articles, both students used the conceptual metaphor DISEASE IS AN ENEMY with phrases like "fight cancer" and comparisons of immune cells to "defenders of the body" or "soldiers." This added emotional appeal and allowed the students to focus on potential applications of their research rather than technical details.

3.3 Conventional Metaphor

Both the journal articles and magazine articles employed highly conventional "dead" metaphors. Examples from students' fields include magnetic "fields," chemical "bonds," and reaction "pathways" in chemistry, or "artifacts" in MRI, the therapeutic "window," and "hallmarks" of aging in biomolecular engineering.

In journal articles, students rarely defined these terms, perhaps assuming they were familiar for their audience. In the magazine articles, students made a distinction between common terms that even a general audience would be familiar with and more technical jargon. Students would either leave technical jargon out altogether in favor of a more audience-friendly synonym or would define key terms, often using a metaphor as in the example for CO_2 carriers below. In the journal article, the student never defined carrier, perhaps assuming that a specialist audience would easily understand this term. In contrast, she elaborated on this "dead" metaphor to explain the technical jargon for the magazine readers. Thus, the student has taken a term that was not understood metaphorically in the journal article and made the figurative comparison more salient in the magazine article.

<u>Example 1 from magazine article</u>: The CO_2 carriers act just like carts: you load it with CO_2, and when you want to unload it, you can take CO_2 out from it. Then, the cart will be empty again ready for another load.

Students also used common phrases and idioms throughout both the journal article and magazine article. For example, the students might explain that new research “shed light on” a particular topic or describe the research “direction” or “approach” in their fields. They also used common transitions to structure the overall narrative of their articles (e.g. on the one hand . . . on the other hand). As the students made no effort to define, explain, or otherwise highlight these metaphors, it is unlikely their metaphorical meanings were particularly salient for them.

3.4 Creative Metaphor

Creative metaphor appeared almost exclusively in the magazine articles, often serving an explanatory function. In the example below, the student uses the metaphor of friends for molecules and hands for bonds to help the reader understand the process of dehydrogenation in chemistry. Since the student wants to introduce a term that may be unfamiliar technical jargon for the reader, she uses a more familiar and concrete source domain (playing with a friend) to make the concept more accessible. This example also starts with a metaphor signal and includes personification as the student writes about “ethane’s hands” which need to “drop” hydrogen atoms for this chemical process.

<u>Example 2 from magazine article</u>: Imagine you want to form a circle with your friend hands in hands, but both of your hands are full of toys. You need to put down the toys before taking your friend’s hand. In this case, ethane’s hands are full of hydrogen atoms, so it need to drop the hydrogen atoms at the first step, we call this process as “dehydrogenation”.

Similarly, in the example below, the student uses the metaphor of a wrinkle in a carpet to explain dislocations and hydrogen embrittlement. Because the paper is about high-entropy alloys, the student purposefully explains several technical terms and processes using metaphor. Although the explanation may still seem technical, it helps a general audience visualize the molecular structure within metals using a more familiar and concrete domain (a rug).

<u>Example 3 from magazine article</u>: We can imagine a layer of atoms as a carpet on the floor and you want to move it, which is plastic deformation. If you drag it directly, you must work hard because of friction. However, you can make a wrinkle on the carpet. Then, you can move the carpet easily by pushing the wrinkle across the floor, because the friction happens only between a small section of the carpet. A dislocation is like this wrinkle, and it helps metallic materials deform easily but also decreases their strength. . . Hydrogen atoms exist like some stones on the carpet to stop the movement of a wrinkle. Then the materials become brittle.

In another example of creative metaphor below, the student explains that a benefit of using vortex trapping over electroporation is that it is faster. He uses the metaphor of adding sugar to a cup of coffee, an activity that is much more familiar to a general reader.

Example 4 from magazine article: You can think of this as adding sugar to coffee. If you add the sugar but do not mix it, some sugar will dissolve into the coffee quickly, but most will sit at the bottom of the cup, waiting for you to finish the bitter coffee. Sure, if you left the coffee indefinitely, all the sugar would dissolve eventually, but then the coffee becomes cold. By mixing the coffee after adding sugar, you can ensure the sugar is better distributed and dissolves much quicker, and you can drink a delicious, hot cup of coffee. By agitating the solution of biomolecules with cells, we can quickly deliver the cargo into the cell, as opposed to waiting on the natural pace of diffusion.

While most of the students' creative metaphors help the reader understand complex scientific ideas through more concrete and relatable source domains, the example below explaining immunotherapy might be confusing. First, as architects design buildings but do not usually supervise the workers, the mapping from the source to target domain is perplexing. Moreover, if the construction workers are the immune cells in this example, it is not clear exactly what the body's "architects" are supposed to represent here. In this case, perhaps a different metaphor or a more literal explanation would be more accessible for the reader.

Example 5 from magazine article: You can think of our immune system as a bunch of people working together to build a house. In the beginning, you're going to have one or two architects design and guide the structure. Then you're going to need many construction workers to physically build the house plank by plank. What we're doing here is attempting to guide that process. When the body is dealing with illnesses like tumors, its architects may not know how many immune cells it needs to deal with the problem. Like architects building their first house, they may undershoot the number of workers they need. So, we come in with ways to let the immune system know how much effort and what type of effort it will need to accomplish its goal.

Overall, students seemed to use creative metaphor to translate their research for a general audience. As they might have assumed the reader would be unfamiliar with specific terms and concepts, the students used more familiar and concrete source domains that would help the reader grasp these new ideas.

3.5 Personification

Personification is a type of metaphor that attributes human characteristics to something nonhuman, and it appeared in both the journal articles and the magazine articles. In the journal articles, personification helped students explain the mechanisms behind scientific observations. For example, a paper on vortex trapping described "populations and subpopulations" of cells "migrating and getting trapped" in a unique geometric design. Journal articles that featured chemical reactions described how elements "acted on" or "attracted" each other to explain their "behaviors" and interpret the results of the experiments. Students also personified their own research and other research studies, for example by explaining that other studies "suffer from" constraints or “sacrifice” external validity when highlighting the research gap their study addressed.

In the magazine articles, students employed personification to explain scientific concepts and processes, sometimes with a more deliberate approach as shown in the example below. The student describes the pulmonary valve as a “single-direction door” and explains why high pressure in the lungs for pulmonary arterial hypertension (PAH) patients can strain the heart. This example also starts with metaphor signaling (you can imagine) to alert the reader that a scientific explanation is coming.

Example 6 from magazine article: You can imagine the heart is a pump, and it pumps blood through the pulmonary artery and into the lungs, where the blood absorbs oxygen and is transported throughout the body. And there’s a little single-direction door called the pulmonary valve that can prevent blood from leaking backward into the right ventricle. Then you will realize why high pressure in the lung increases the burden on the patient's heart. The heart might start by gently pushing the door open to pump the blood to the ends of our bodies, but now someone is blocking it on the other side of the door, and the heart needs to fight that guy and push the door as hard as it can. Until one day, our hearts just don't have the strength anymore.

Other students took a more creative approach and seemed to use personification to appeal to the magazine readers. For example, one student described climate change as an “uninvited monster” to add drama and interest to the opening of her magazine article. Another student introduced the reader to the debris disks she studies in outer space by writing the entire article from the point of view of a single grain of the debris disks she studies in outer space.

3.6 Metaphor Signaling

In this study, metaphor signaling appeared in both types of articles, though it was much more common in the magazine articles than the journal articles. As noted above, the students might not feel that technical terms in their journal articles were particularly metaphorical and thus would not warrant any special kind of signaling. However, students occasionally used metaphor signals in the journal articles as well. In the example below, the student uses “as” to help the reader anticipate the metaphor that cytokines are the “language” of the immune system. Even so, the student ends the statement with a citation, so the metaphor appears more objective.

Example 7 from journal article: Cytokines act as the language of the immune system by communicating signals between immune cells.[2]

Later in the same paper, the student describes the research gap she wishes to address by explaining that certain immunocytokines used in immune therapy have a short half-life in the body. In the example below, the student puts quotation marks around the word “sink” to signal its metaphorical usage for the reader. The quotation marks may also indicate that this is a theoretical and as yet unproven explanation.

Example 8 from journal article: Many researchers have speculated about a possible IL-7 “sink” contributing to its diminished effects when injected *in vivo*.[5] While the mechanism of this “sink” is not yet fully understood, IL-7 diminishes in the body after a short time.[5]

In the magazine articles, students often signaled metaphor with terms such as like, quotation marks, or introductory phrases (e.g. let’s say/imagine that). This metaphor signaling almost always accompanied creative metaphors that explained complex scientific concepts for the reader. For example, when a student described the needle brush structure of carbon nanotubes in his magazine article, he used quotations around words such as “soft needles” and “needles’ heads” to set the metaphor apart as something special.

Skorczynska and Ahrens [29] found that writers use metaphor signaling and metaphor in scientific magazine articles to help the reader understand explanations for scientific concepts. Similarly, the students in this study appeared to use metaphor signaling to help their general audience anticipate explanations of complex scientific ideas.

3.7 Extended Metaphor

Extended metaphor, or the same overarching metaphor repeated throughout a passage, can help explain a complex idea in simple terms, as seen in the creative metaphor examples above, or can be used to evoke emotions and imagery for the reader. Although extended metaphors were more common in the magazine articles, students employed them effectively in the journal articles as well. For example, one student repeatedly used the metaphor of lengthening the “window” of immunotherapy treatment to keep the focus on potential applications of her research throughout her journal article.

Compared to the journal articles, the students were more likely to structure the magazine articles around an overarching extended metaphor with catchy titles like “Empowering the human immune system against its deadliest enemy,” or “The smallest cells keep age-old secrets.” One student titled her article “A poorly made Martian parfait” and centered the entire article around the comparison of layers of rock on Mars to layers of fruit, yogurt, and granola in a parfait. As shown in the diagram below, each layer of the parfait represented a different type of rock/mineral in layered deposits on Mars. The mystery of out of place ingredients represented the key research question the student was trying to solve – why some rocks/minerals were found in unexpected locations, with rocks/minerals from older time periods appearing in layered deposits on top of rocks/minerals from newer time periods. Although structuring the entire article around this one metaphor may have gone too far, the student appeared to be trying to appeal to her audience with a more familiar and relatable scenario.

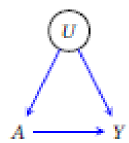
Example 9 of extended metaphor from magazine article:

Source Domain: *Parfait*		Target Domain: *Minerals/Rocks on Mars*
Parfait Layers	→	Layered Deposits
Yogurt on Bottom	→	Oldest Noachian Rocks/Minerals
Fruit in the Middle	→	Hesperian Rocks/Minerals
Granola on Top	→	Newest Amazonian Rocks/Minerals
Out of Place Items	→	Locations that Don’t Match Timeline

3.8 Visual Metaphor

Visual metaphor appeared most commonly in the journal articles, which used visuals like graphs and diagrams to represent scientific processes and data. For example, a student who wrote a meta-analysis on how causal inference could be applied to studies on human-robot interaction in the medical field used causal graphical models like the one below to visually represent many different situations. In the abstract, this student wrote that he wanted researchers outside his field to view causal inference as a tool for human-robot interaction practitioners in observational settings. The visual metaphors like the graphical model below would help these outside researchers understand the various scenarios posed throughout the paper. In addition, the student wrote that this well-known example is called the "bow-arc problem," where some unobserved confounder (U) makes it difficult to interpret the causal effect between two experimental variables (A, Y). The shape of the model looks like a stringed bow, adding another layer to the visual metaphor.

Example 10 from journal article:



While all the journal articles included visual metaphor, most of the scientific magazine articles did not. This is similar to [19] who noted that when an academic article was translated for a more general audience, the data visualizations were removed and replaced with appealing images instead. Likewise, the students in this study appeared to remove the data visualizations to appeal to a more general audience who may not want specific data from their research or may feel intimidated by complex graphs and models.

4. Conclusion

This study analyzed how students in a graduate-level engineering writing and communication course used metaphor to communicate when writing for both specialist and non-specialist audiences. Students used a similar amount of metaphor in their journal articles and scientific magazine articles, but seemed to adjust their metaphors to appeal to different audiences. It appears the students assumed their readers had a strong background in their fields for the journal articles as they employed conventional metaphor and visual metaphor to communicate technical details and results. On the other hand, it seems like the students assumed their readers had little background and less interest in their fields in the scientific magazine articles as they employed more extended and creative metaphors to explain scientific concepts and maintain the reader's attention.

Students said they enjoyed discussing metaphors in the articles from *The Best Science and Nature Writing* and from their fields on the course discussion board and in class. They said they enjoyed writing more creatively in the scientific magazine articles and could see real-world applications of being able to discuss their work on interdisciplinary teams, at networking events, or with their close family and friends outside of their fields. Therefore, one key implication of this study for educators is the need to focus on multiple audiences in graduate-level writing and communication courses. While students may express the most interest in writing and publishing papers for highly technical academic journals, they will need to communicate with multidisciplinary audiences and translate their research for multiple contexts regardless of whether they stay in academia or go into industry in the future.

Although the results presented here come from a specific group of students in a specific course, they suggest that engineering graduate students in other contexts may also be receptive to writing courses that focus on metaphor in scientific writing. Instructors may find their engineering students appreciate metaphor more if they emphasize how metaphor informs fixed expressions in their fields, how metaphor helps scientists process abstract information, or how metaphor can translate their research for the public. In addition, students can analyze models like the articles from *The Best Science and Nature Writing* or research articles from well-known academic journals to better understand the role of metaphor in communicating science in a variety of contexts.

References

[1] G. Lakoff and M. Johnson, *Metaphors we live by*. Chicago, IL: University of Chicago Press, 1980.

[2] G. Lakoff and M. Johnson, *More than cool reason: A field guide to poetic metaphor*. Chicago: University of Chicago Press, 1989.

[3] G. Lakoff and M. Johnson, *Philosophy in the flesh: the embodied minds and its challenge to western thought*. New York: Basic Books, 1999.

[4] G. Steen, "From linguistic to conceptual metaphor in five steps," in *Metaphor in Cognitive Linguistics*, R. Gibbs and G. Steen (Eds), Amsterdam: John Benjamins, 1999, pp. 57 – 77.

[5] Z. Kövecses, *Metaphor: A practical introduction*, *2nd edition*. Oxford: Oxford University Press, 2010.

[6] D. Gentner, "Metaphor as structure mapping: the relational shift," *Child Development*, vol 59, pp. 47 – 59, 1988, doi: 10.2307/1130388.

[7] D. Gentner and B. Bowdle, "Convention, form, and figurative language processing," *Metaphor and Symbol*, vol 16, pp. 223 – 247, 2001, doi: 10.1207/S15327868MS1603&4-6

[8] G. Fauconnier and M. Turner, *The way we think: Conceptual blending and the mind's hidden complexities*. New York: Basic Books, 2003.

[9] T.L. *Brown. Making truth: Metaphor in science*. Champaign, IL: University of Illinois Press, 2003.

[10] C. Müller, "Waking metaphors: Embodied cognition in multimodal discourse," in *Metaphor: Embodied Cognition and Discourse*, B. Hampe (Ed), Cambridge: Cambridge University Press, 2017, pp. 297 – 316.

[11] A. Deignan, E. Semino, and S. Paul, "Metaphors of climate science in three genres: Research articles, educational texts, and secondary school student talk," *Applied Linguistics*, vol. 40, issue 2, pp. 379 – 401, 2019.

[12] G.J. Steen, *Visual metaphor: Structure and process*. Amsterdam: Johns Benjamins Publishing Company, 2018.

[13] E. El Refaie, *Visual metaphor and embodiment in graphic illness narratives*. New York, NY: Oxford University Press, 2019.

[14] C. Reeves, *The Language of Science*. New York, NY: Routledge, 2005.

[15] A. S. Reynolds, *Understanding Metaphors in the Life Sciences.* Cambridge: Cambridge University Press, 2022.

[16] M. Bradie. “Science and metaphor,” *Biology and Philosophy*, vol. 14, pp. 159-166, 1999, doi: 10.1023/A:1006601214943.

[17] T.L. Brown, *Making truth: Metaphor in science*. Urbana, IL: University of Illinois Press, 2003.

[18] E.F. Keller, “Cognitive functions of metaphor in the natural sciences,” *Interdisciplinary Science Reviews*, vol. 45, no. 3, pp. 249-267, 2020, doi: 10.1080/03080188.2020.1794384.

[19] A. Deignan and E. Semino, “Translating science for young people through metaphor,” *The Translator*, vol. 24, no. 4, pp. 369 – 384, 2019, doi: 10.1080/13556509.2020.1735759.

[20] A. Auge, “Ideological and explanatory uses of the COVID-19 as a war metaphor in science,” *Review of Cognitive Linguistics*, vol. 20, no. 2, pp. 412 – 437, 2022, doi: 10.1075/rcl.00117.aug.

[21] C. Taylor and B. M. Dewsbury, “On the Problem and Promise of Metaphor Use in Science and Scientific Communication,” *Journal of Microbiology and Biology Education*, vol. 19, no. 1, pp. 1-5, 2018, doi: 10.1128/jmbe.v19i1.1538.

[22] S. Brown and S. Salter, “Analogies in science and science teaching,” *Advances in Physiology Education*, vol. 34, 167 – 169, 2010, doi:10.1152/advan.00022.2010.

[23] M. Pigliucci and M. Boudry, “Why machine-information metaphors are bad for science and science education,” *Science and Education*, vol. 20, pp. 453 – 471, 2011, doi: https://doi.org/10.1007/s11191-010-9267-6.

[24] K. Niebert, S. Marsch, and D. F. Treagust. “Understanding needs embodiment: A theory-guided reanalysis of the role of metaphors and analogies in understanding science,” *Science Education*, vol. 96, no. 5, pp. 849–877, 2012, doi: 10.1002/sce.21026.

[25] A. Harrison, and O. De Jong, “Exploring the use of multiple analogical models when teaching and learning chemical equilibrium,” *Journal of Research in Science Teaching*, vol. 42, no. 10, pp 1135 – 1159, 2005, doi: 10.1002/tea.20090.

[26] Pragglejaz Group, “MIP: A Method for Identifying Metaphorically Used Words in Discourse,” *Metaphor and Symbol*, vol. 22, no. 1, pp. 1–39. doi:10.1080/10926480709336752.

[27] G.J. Steen, A.B. Dorst, A. Herrmann, T. Kaal, T. Krennmayr, and T. Pasma, *A Method for Linguistic Metaphor Identification*. Amsterdam: John Benjamins, 2010.

[28] I. S. Barrios, “A review of studies about conceptual metaphors in science and science education,” *Revista de Investigación Educacional Latinoamericana*, vol. 58, no. 1, pp 1-15, 2021.

[29] H. Skorczynska, and K. Ahrens, “A corpus-based study of metaphor signaling variations in three genres,” *Text and Talk*, vol. 35, no. 2, pp. 359 – 381, doi:.1515/text-2015-0007.