Improving University Life Science Instruction with Analogies: Insights from a Course for Graduate Teaching Assistants

Sara Petchey,[†]* David Treagust,[‡] and Kai Niebert[†]
[†]Institute of Education, University of Zurich, Zurich 8001, Switzerland; [‡]School of Education, Curtin University, Perth 6845, Australia

ABSTRACT
Abstract concepts dominate university science teaching, and much of this content is taught without sufficient connection to students' prior knowledge or everyday experiences. As this can be problematic for students, the aim of this research was to determine the utility and effectiveness of a professional development module on using analogies to make these important connections for learning. We conducted qualitative content analysis of analogies in teaching plans designed by 75 graduate teaching assistants who participated in the module between 2018 and 2021. The module is part of a course on Teaching Science at University (TSU) and pairs cognitive science with a structured analogy design tool, originally developed for K–12 education. Most course participants used the tool systematically and developed analogies linking abstract science target concepts with students' everyday experiences; however, some analogies contained a high cognitive load or unaddressed anthropomorphic logic that might negatively impact learning. Participants' reflections on their learning in the module suggested a new awareness of the need for planning and for active student discussion of analogies, particularly where they break down. This research has shown that TSU's stepwise guidance using a structured pedagogical tool for planning and teaching with analogies is highly suitable for higher education.

INTRODUCTION
Analyses of the experiences of students in the science, technology, engineering, and mathematics (STEM) fields suggests they often find the teaching in these fields to be information heavy, nonparticipatory, and lacking in everyday application (Johnson, 2007; Seymour and Hunter, 2019). Indeed, the science concepts taught at the university level are complex, abstract, often unfamiliar, and difficult to understand. They are indirect conceptions and theories developed through scientific inquiry or based upon observation only possible using tools such as modeling and microscopes (Niebert *et al*., 2012). As a result, science teaching often lacks a direct connection to students' everyday experiences or knowledge—the very things constructivist learning theory tells us learning should build upon. For example, because a direct experience of atomic orbital shapes or the phases of the polymerase chain reaction is not possible, we propose that analogies can provide the missing links to student everyday knowledge and experience in our teaching. We define an analogy in this paper as a bridge between two domains—the analogue (typically something from everyday life) and the target science concept (something that would be found in our curricula).

Connecting Teaching to Bodily Experiences Facilitates Learning
In the 1980s, linguists began exploring how abstract concepts—like science concepts—are understood. Their main finding was that all understanding is based on bodily or cultural experience (Lakoff and Johnson, 2008). This understanding takes place either directly when an experience is made, or indirectly when we build a bridge via an analogy from a previous experience to the abstract concept. This suggests

Elisabeth Schussler, *Monitoring Editor*
Submitted Jul 20, 2022; Revised Mar 3, 2023; Accepted Mar 10, 2023
CBE Life Sci Educ June 1, 2023 22:ar24
DOI:10.1187/cbe.22-07-0142
S.P. was responsible for conducting the TSU courses, conceptualizing the research, data collection, co-coding all the data, and co-writing the paper. D.T. co-wrote the paper. K.N. was responsible for co-conducting the TSU courses, conceptualizing the research, co-coding the deductive qualitative content analysis, and co-writing the paper.
*Address correspondence to: Sara Petchey (sara.petchey@mnf.uzh.ch).

analogies are not only a linguistic phenomenon but also reflect general principles of understanding, and that referring to everyday experience and using analogies are not just a matter of figurative language but are conceptual in nature (Lakoff and Johnson, 2008). Embodied cognition takes the viewpoint that the cognitive processes involved in understanding occur not only in our brains but also through our bodies and their interactions with the physical and cultural environments (Lakoff, 2012; Niebert and Gropengiesser, 2015). This perspective contrasts the traditional approach to the body as a "peripheral input and output device" (Wilson, 2002, p. 625) and is growing in popularity (Kolovou, 2022).

If experience plays such a crucial role in understanding, a closer look at how this takes place may be worthwhile. Human experience takes place in the so-called mesocosm, a world of middle dimensions: medium distances and times and low velocities and forces (see Figure 1). Whereas sensory perception and experience in general primarily take place in the mesocosm, scientific evidence and theories often exceed the mesocosm. Structures such as the biosphere and the solar system are not part of the mesocosm but are of macrocosmic scale. Our cognitive system is not adapted for direct perception at these dimensions. The same holds for (sub)microcosmic structures such as cells or molecules. Though we cannot change the scale of science concepts, we *can* use tools to bridge the gap between what is perceptible and imperceptible. Technology is one such tool; for example, a microscope can extend the boundaries of the mesocosm and make the microscopic directly perceptible. Analogies are another such tool, enabling us to connect the imperceptible to things we can directly sense, experience, remember, imagine—familiar elements from everyday life. Well-structured analogies tap into the critical role bodily perception can play in understanding at school and university levels (Niebert and Gropengiesser, 2015).

Analogies as Teaching and Learning Tools

What we know from research on teaching and learning with analogies is that examples such as "the cell is like a factory" or "electricity is like flowing water" can help students visualize complex, abstract science concepts by pointing to similarities with observable physical structures and events. The familiar analogues (here, a factory and flowing water) help students see the abstract idea in simpler, more familiar terms and draw upon knowledge they "own and trust" (Harrison and Coll, 2008, p. 47). Analogies increase the perception of relevance, aid recall (Halpern *et al.*, 1990), motivate students (Duit, 1991), and spark further inquiry (Treagust *et al.*, 1996; Glynn and Takahashi, 1998). Analogies are also useful at the university science level, as they encourage students to see abstract concepts as systems of relationships rather than discrete facts or sets of procedures. This is the difference between students knowing what steps to follow to complete a mathematical algorithm versus students also understanding the algorithm's function and purpose. Research suggests this sort of relational thinking generally acts as the "cognitive underpinning of higher order thinking" and is critical to students' development of expert-like thinking (Richland and Simms, 2015, p. 177). Analogies are also valuable tools in conceptual change and inquiry learning (Duit, 1991), make abstract scientific theorizing generally possible (Lakoff and Núñez, 2000), and can "suggest new questions, relationships, and investigations" (Harrison and Coll, 2008, p. 169).

All analogies function in a similar manner: Elements of the analogue are mapped to the target concept to facilitate understanding. This function involves making inferences about similarities and differences in structure and function between a typically concrete analogue and an abstract target concept. To clarify what this means, we refer to the following model analogy: mass spectrometry is like the time needed to walk home from the grocery store (from Participant 21S8). Here, the target science concept is mass spectrometry, an analytical technique that helps identify chemical substances in a sample by sending them on a path through electric and magnetic fields. The movement behavior of the substance will uniquely vary according to its mass and charge, which allows it to be identified in this process (Beynon and Brown, 2023). Spectrometry is certainly not an everyday experience for most people, so it is a suitable topic for using an analogy that is in the learner's everyday experiences. In contrast, the analogue here, walking home from the grocery store, is a mesoscopic, concrete, familiar, embodied action that students of all backgrounds (cultural, prior levels of knowledge) would be able to not only remember, but also know through personal experience. Students could imagine why such a trip might take more or less time according to the weight of the groceries they

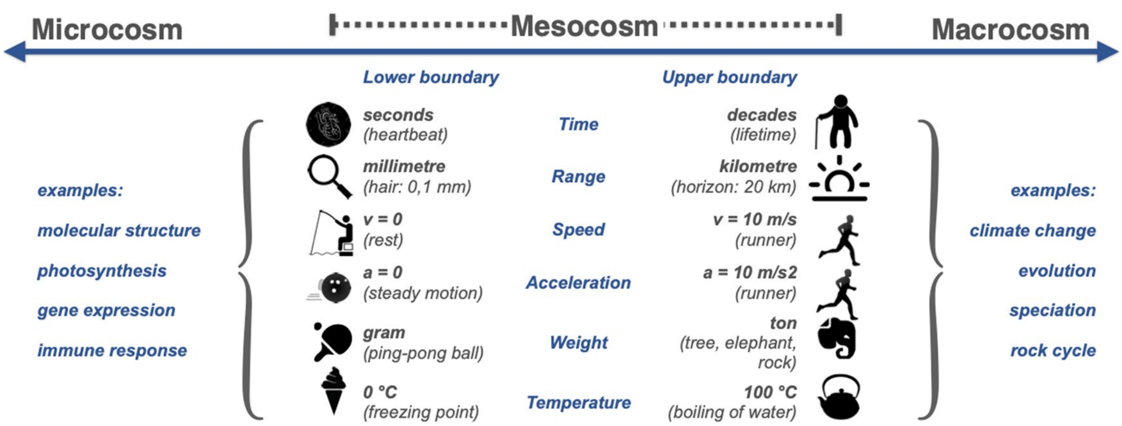

FIGURE 1. Dimensions and boundaries of the mesocosm.

must carry and the "attractiveness" of the other shops they might like to visit along the way home, then make inferences about the analogous travel of substances in the process of spectrometry.

Though analogies can greatly benefit learning in science, they can also lead to undesirable outcomes such as overgeneralizations, alternative conceptions (wherein ideas differ from accepted scientific beliefs), or inadequate conceptions (Glynn, 2008). Some students may not understand that analogies have limits in the degree to which they can accurately describe reality (Cvenic *et al.*, 2021). Analogies taken too far or too literally can suggest or reinforce false associations between the target concept and the analogue (Curtis and Reigeluth, 1984; Harrison and Treagust, 2006). This is often the case when the analogue and target concept share many superficial similarities (known as "near analogies"); near analogies can be more problematic than those in which the analogue and target concept, at first glance, do not seem to have anything in common (known as "far analogies"; Gentner, 1983; Halpern *et al.*, 1990). These unhelpful outcomes are due to the fact that students are vulnerable to making errors when mapping, because they often lack the ability to assess the saliency of one characteristic of the analogy over another; sometimes they do not recognize when an aspect of the target concept has no equivalent in the analogue or vice versa but nevertheless create a connection. These mapping errors can lead to the development of inadequate or erroneous conceptions *if* there is an absence of systematic guidance during the lesson (Niebert *et al.*, 2012).

Additionally, analogies can make learning more difficult by increasing the cognitive load of the learning task. This occurs, for example, when the analogue is less cognitively accessible or more complex than the target science concept in the first place (Dagher, 1995) or when the analogue is culturally unfamiliar. In these cases, the student must first become acquainted with the analogue before it becomes useful for deconstructing the science concept. Thus the choice of analogue is a critical step of analogy development, and choosing an analogue that is embodied, that is, based on a direct bodily or cultural experience, is a good way to ensure accessibility (Niebert *et al.*, 2012).

Effective Use of Analogies Requires Systematic Guidance

So how well do teachers navigate the fine line between helpful and unhelpful use of analogies in the classroom? Research suggests analogies are most powerful when they are well prepared but finds that secondary school teachers most often use analogies spontaneously when trying to explain something in a different way or to give students a sense of familiarity with an unknown concept (Venville and Treagust, 2002). Research also suggests that elaborate analogies with systematic, detailed mapping by students provide a rich context for learning and ensure students interpret the analogy as intended by engaging them in critical thinking about the utility and limits of the analogy (Holyoak, 2005; Glynn, 2008). However, teachers often use analogies in a more limited manner, for example, to present a quick similarity—that the nucleus of a cell is like a computer that controls the cell's activities—without going into more detail (Venville and Treagust, 2002). In sum, studies of secondary school teachers' use of analogies find that their practice often does not align with what we know about teaching effectively with analogies.

This gap between ideal and actual use of analogies in teaching led to the creation of the FAR guide, a tool intended to help teachers improve their teaching with analogies (Treagust *et al.*, 1992; Venville, 2008). "Because students have difficulty recognizing the relational and explanatory power of an analogy, they often miss the real point of the analogy, and this is an excellent reason for teachers to use a systematic approach when teaching with analogies" (Treagust *et al.*, 1998, p. 87). The FAR guide is an empirically developed tool, developed after 10 years of studying teachers' use of analogies (Venville, 2008). It breaks down the creation and use of analogies into three phases: *F*ocus (what happens before class), *A*ction (during class), and *R*eflection (after class; see Table 1). The focus stage guides careful consideration of the topic to be taught, students' prior knowledge of the target, and students' familiarity with the chosen analogue. Here the authors of the FAR guide intentionally shifted as many steps of analogy design into this pre-teaching "focus" phase after their experience that preceding analogy teaching models had shown that even experienced teachers forgot one or more operations during live teaching. "We believe that limiting the in-class operations to discussing the familiar analogy's likes and dislikes increase the likelihood of these critical operations being completed on a regular basis" (Treagust *et al.*, 1998, pp. 91–92). In the action stage, the shared attributes of the target and analogue are mapped, then analysis turns to where the mapping no longer works/where the analogy breaks down.

In the final reflection stage, the clarity and usefulness of the analogy are considered (Harrison and Coll, 2008).

TABLE 1. The FAR guide to teaching with analogies (Treagust *et al.*, 1998)

Focus	**Before class**
Concept	What makes a concept abstract or difficult to understand?
Students	What prior knowledge do students have on the topic?
Analogue	Make sure students are familiar with the analogue.
Mapping	Check where analogue can be mapped to target—and where not.
Action	**In class**
Familiarity	Check students' familiarity with the analogue.
Likes	Discuss the aspects of the analogue that can be mapped to the target concept.
Unlikes	Discuss where the analogy breaks down.
Reflection	**After class**
Conclusion	How useful and clear was the analogy?
Improvements	How can you improve instruction with the analogy?

Teaching Graduate Students the Use of Analogies for Higher Education

So far we have established that teaching abstract concepts typical of STEM fields and teaching effectively with analogies are challenging tasks. Both are especially challenging when one is trained primarily as a research scientist and has little background in pedagogy, as is true of many graduate teaching assistants (GTAs) in the life sciences. With the needs of this population in mind, we created a professional development course called Teaching Science at University (TSU) at the University of Zurich. Our drive to develop the course also came from our observation that subject-specific pedagogical development opportunities were generally lacking in higher education and from research suggesting that subject-specific pedagogical knowledge known as pedagogical content knowledge (PCK) is associated with student learning (at least in K–12; e.g., Hattie, 2009; Coe *et al.*, 2014; Neumann *et al.*, 2019). PCK is specialized knowledge about teaching that falls at the intersection of disciplinary expertise (content knowledge, CK) and general pedagogical knowledge (PK; Shulman, 1986). PCK includes knowing how to tailor teaching to a specific topic or discipline, audience, and classroom context and knowing which analogies, examples, or explanations make a topic comprehensible to particular students (Shulman, 1986; Carlson and Daehler, 2019). We also know that instructors at the start of their teaching careers have little PCK (van Driel *et al.*, 1998; Lee and Luft, 2008; Krepf *et al.*, 2018).

TSU's five modules focus upon a mix of general (PK) and discipline-specific (PCK) pedagogical topics, ranging from evidence-based teaching, conceptual change, inquiry learning, and socioscientific issues to teaching with analogies. The research we present in this paper focuses on TSU's analogy module, in which we integrate empirical research findings on effective teaching with analogies and the theory of embodied cognition. Key learning goals of the module are for participants to learn about and practice analogy design that builds upon what we know from research about effective analogies and to recognize student learning can be better facilitated when it is connected to bodily or cultural everyday experiences (i.e., embodied cognition; Johnson, 2015). This combination of empirical and theoretical appeals to the scientific background of our participants, who value evidence-based practices and teaching strategies in step with modern understanding of sense-making and learning.

Research Aims and Question

Descriptive accounts or analysis of how pedagogical tools are perceived and used by scientists teaching in higher education are rare. University instructors' use of analogies has not yet been thoroughly explored, and we are not aware of any other professional development courses or research programs in higher education settings that use the FAR guide. In previous research on TSU, we found that scientists new to pedagogy appreciated structured tools for conceptual change teaching (Petchey and Niebert, 2021). In this paper, we look at their use of a structured tool for teaching with analogies. We are interested in both the effectiveness of this tool and the fit of our analogy module at the university level. In this research, we ask: How does a structured tool influence graduate students' plans for teaching with analogies in the life sciences?

METHODS

Study Population

Our data came from 75 participants in six separate semesters of the TSU course between 2018 and 2021. They initiated their own participation in the course and earned credit points for course completion (e.g., for PhD programs). Our study population was balanced in terms of gender and came from a variety of life science and national backgrounds. All participants were PhD students with teaching roles as GTAs at the University of Zurich, a research-intense, public university. Participants had low levels of experience as GTAs and nearly no teacher education before the course. It is important to note that they were not pre-service teachers, but rather, they primarily aspired to be successful life science research scientists. Nevertheless, they were expected to conduct a significant amount of teaching of undergraduates and wanted to do so well. We know from previous research on GTAs that a course like TSU can help GTA populations develop confidence and start to view their teaching assignments as manageable (Smith and Delgado, 2021). Our course was most participants' first contact with pedagogy.

Data Collection and Informed Consent

We administered a pre-course survey to assess participants' backgrounds and needs and also to introduce our research and ask if participants would like to make their data available for our study. It was made clear that everyone could participate fully in the course regardless of their choice to release their data, all could withdraw their data from our study at any time without any disadvantage in TSU, and the data would be fully anonymized.

At the end of each module of the course, participants completed an assignment in which they applied the pedagogical tool or principles that they had learned (PK) to their own teaching context, students, and subject (PCK). The analogy module assignment consisted of six steps that followed the FAR guide from choice of science concept (1), design of the analogy (2, 3), plan of the analogy's mapping (4), and reflection (5, 6). We collected the assignment text from the course and anonymized it, removing participant and supervisor names and any identifying details such as institute name or course title. The collection and use of these data were deemed ethically sound according to the criteria set out by our Institutional Review Board and was approved in 2018 (University of Zurich, 2014).

Data Analysis

We used qualitative content analysis to analyze the participants' analogy assignments (Mayring, 2002). We chose this methodology, because other researchers papers have proven it to be adequate for analyzing analogies (Niebert *et al.*, 2012; Niebert and Gropengiesser, 2015). More specifically, we use both deductive and inductive qualitative content analysis. The former enabled us to bring previously formulated categories derived from theory in connection with the text to be analyzed; the latter resulted in categories as near as possible to the data—in other words, categories that sound like the words, experiences, and thoughts of their authors (Mayring, 2014).

We were careful to address potential bias in the analysis due to the fact that the first author (S.P.) conducted the TSU courses and was the primary researcher responsible for data collection and co-coding during the analysis. First, the assignments were collected after the participants had completed TSU, and our analysis was carried out after complete anonymization of the data. Additionally, we involved a total of four researchers in the coding process: the first author (S.P.); the last author (K.N.), who has extensive expertise in teaching with analogies and produced the online course videos but was not involved in conducting the course otherwise; and two additional education researchers with no involvement in TSU.

In the first stage of analysis, we used deductive coding to look at questions 1–4 in the analogy assignment that guided participants' design of analogies (i.e., choices of science concept and analogue). The first and last authors (S.P. and K.N.) first determined the coding categories based upon research findings on effective analogy design with respect to the use of the mesocosm (Niebert and Gropengiesser, 2015; see Table 2), level of embodiment (Niebert *et al.*, 2012; see Table 3), familiarity of the analogue (Niebert and Gropengiesser, 2015; see Table 4), and risk of overinterpretation (Gentner, 1983; Halpern *et al.*, 1990; see Table 5). On one level, we chose these constructs and prior findings due to their direct relevance to both the educational content and the structured analogy design tool in TSU. At perhaps a more meaningful level, these constructs and findings also help us judge the utility of our tool in helping people design analogies that stand up to research findings on embodied cognition and its connections to learning as well as findings that identify problematic aspects of learning with analogies. Participants' assignments were then evaluated independently by the first author (S.P.), last author (K.N.), and the third coder (no TSU involvement). During the initial analysis, we noticed a prevalence of problematic anthropomorphic logic; we therefore added a round of deductive analysis to detect presence and participant awareness of anthropomorphism in their analogies. We defined anthropomorphism as instances in which nonhuman organisms or inanimate objects are described as having human properties, especially intentional/goal directedness (Tamir and Zohar, 1991; Betz *et al.*, 2019), and we looked in particular for objects paired with active verbs and a context of intention, choice, or desire.

In the second stage of analysis, the first author (S.P.) and the fourth coder used inductive coding to analyze questions 5 and 6 in the analogy assignment by conducting an open-ended analysis of the participants' responses to reflection prompts on anticipated student learning through the analogy and the changes in their thoughts or experiences around teaching and learning with analogies. We read the participants' answers, then cooperatively built (and reorganized when necessary) the coding categories according to the concepts and ideas they raised.

The researchers completed all coding work following a detailed coding manual. Relevant details of the manual have been included in the results Tables 2, 3, 4, and 5, and the full manual is available in the Supplemental Material. In both the deductive and inductive coding processes, we came to consensus through communicative validation in which we discussed coding differences and modified the codes or coding guidelines as necessary until we reached an acceptable interrater reliability (IRR). We calculated IRR by subtracting the number of code decisions for which the coders did not agree from the total number of coding decisions, then divided by the total number of coding decisions. Our IRR for the deductive coding before the validation was 86%, and after, 99%. The inductive coding was done between two researchers simultaneously and collaboratively, following the coding manual and with communicative validation, and IRR was near 100%. We ensured the trustworthiness, credibility, and validity of our qualitative findings through prolonged engagement and persistent observation of participant performance; we collected data from six independent semesters of TSU, with a wide variety of participants and had consistent results (Lincoln and Guba, 1985).

RESULTS

In the following sections we present the results of our qualitative content analysis of participants' assignments as well as their reflections about analogies. Our aim was to assess how well participants' analogies align with course guidance and with research findings on effective analogies. Next to our theory-guided deductive categories, some new inductive categories emerged. We present the additional categories in this *Results* section to improve readability. The participants' reflections gave us information about participants' prior knowledge and understanding about instructional analogies with which we could make cautious interpretations about the analogy module's potential strengths, weaknesses, and overall suitability for higher education. We have organized the *Results* to follow the sequence of design and reflection steps in TSU's analogy module assignment.

Which Target Concepts Warrant the Use of Analogies?

Embodied cognition suggests that abstract target concepts are hard to understand without analogies. Therefore, we encouraged our participants to identify science concepts their students find hard to understand and use them as the target concepts of their analogies. Based on embodied cognition, we analyzed the scale of participants' choices of target concepts to explain why they could be difficult. More than half (55%) were microscopic in scale, occurring at the molecular or cellular level; 16% were macroscopic concepts, occurring at the population, community, global, or universal physical scales or in dimensions of time greater than decades; and 9% were mesoscopic concepts, occurring at the organ or organismal scales and directly observable to humans (see Table 2). Most of the science concepts involved physical or abstract processes, and very few focused solely on concrete physical structures.

Our scale-based coding categories (micro/meso/macroscopic) were quite helpful to categorize the analogies' target concepts. However, we found an additional category within the participant assignments—science concepts relating not to natural entities but to methodologies, both physical (e.g., laboratory procedures) and abstract (e.g., mathematical or computer-based procedures). Similar to GTAs at other institutions, many of our participants teach laboratory or practical courses involving statistics, programming, and/or experimental design. It is therefore logical that they chose target concepts like random sampling, incidence versus prevalence of disease, coding with programming languages, flow cytometry, and cladistics. In fact, 20% of participant assignments featured methodological concepts (18 assignments). Though the methodological category does not align with the scale-based categories proposed by Niebert and Gropengiesser (2015), its inclusion in our analysis was nevertheless important, as it captures an important focal point of higher education/typical GTA teaching.

TABLE 2. Scales of science concepts in participants' analogies (coded by comparison to values in Figure 1, more than one code per assignment was possible)[a]

Scale	Percent (no. of assignments)	Participant examples
Microcosm	55 (48 of 75)	Cellular communication, apoptosis vs. necrosis, DNA mutations
Mesocosm	9 (8 of 75)	Commensalism vs. mutualism, ecological niches, circadian rhythms
Macrocosm	16 (14 of 75)	Adaptation of populations, rock cycle, natural selection
Methodological	20 (18 of 75)	Gel electrophoresis, programming languages, sample size, reproducibility, random sampling

[a]Color code: green, ideal for use in analogies, yellow, not ideal for use in analogies.

Degree and Impact of Embodiment in the Analogue

Participants were next asked to choose an experience-based analogue for their analogies that they believed would be familiar to their students. The majority (69%) chose an analogue with a high or medium level of embodiment. These analogues (i.e., first two rows of Table 3) depicted everyday, mesoscopic experiences that students were likely to have had personally or could easily imagine. This means the analogues were cognitively accessible to students such that they could immediately proceed with making connections between the analogue and the unfamiliar science concept, and no instructional time would be needed to first explain the analogue.

On the problematic side, we coded 9% of the analogues as having a low degree of embodiment in the form of experiences that were hypothetical or at least *not* likely to be familiar from everyday life. This category of analogues tended to have a higher potential cognitive load for students, such as culture-specific references (in five of 75 assignments) or particular situational descriptions (in 22 of 75 assignments) in which the analogue only worked under specific or detailed conditions. Examples included the analogy "protein structure determination by x-ray is like throwing footballs at an invisible DMC DeLorean" (Participant 21S7), which makes a cultural reference to a time traveling car from *Back to the Future*, a movie that may not be familiar to all students; and "flow cytometry is like identifying different types of cars" (Participant 21S24), which was then followed by 120 words to describe the setup of the system to flag, sort, and identify cars, the role of the car's shape or color. This long "analogue" is not ideal, as it would require significant student thinking and working memory. Finally, 21% of the analogues had a very low level of embodiment and were not experience-based at all (see Table 3).

Categorization and Potential Impact of Analogies by Scale

Next, we analyzed the scale (e.g., microscopic, mesoscopic) of the target science concept and of the analogue. Then, based on the different combinations of scale present in the analogies, we developed three categories of analogies: bridge, stationary, and flyover. These categories connect an analogy's design to its possible impact on learning (see Table 4).

TABLE 3. Degree of embodiment of the analogue (only one code per assignment was possible)[a]

Degree of embodiment	Coding criteria	Percent (no. of assignments)	Participant examples
High—a personal experience	Analogue requires students to *remember* something most of them have personally experienced.	44 (33 of 75)	"Protein degradation is like recycling." (19F7) "Algorithms are like cooking recipes." (20S2) "Self-incompatibility in plants is like moving through an airport." (18F8) "Incidence and prevalence of disease are like the water flow in a bathtub." (18F9)
Medium—a potential experience from everyday life	Analogue requires students to *imagine* something realistically from everyday life.	25 (19 of 75)	"Local adaptation is like home team advantage." (18F1) "Brownian motion is like the movement of a large beach ball over a crowd in a stadium." (19S15) "Targeted DNA extraction is like fishing." (19F1)
Low—a hypothetical experience, NOT from everyday life	Analogue requires students to *imagine* a situation *not* from everyday life and possibly artificially constructed.	9 (7 of 75)	"Production of thyroid hormones is like production of toys at a toy factory." (19S1) "X-ray crystallography is like throwing footballs at an invisible DMC DeLorean." (21S7) "DNA gel electrophoresis is like thirsty animals of different sizes walking through the forest." (21S13)
Very low—not experienceable	Analogue does not involve a bodily or cultural experience.	21 (16 of 75)	"Orbitals are like clouds." (18F11) "The body's barrier is like a castle." (18F13) "Chemiosmosis is like a hydroelectric dam." (19S12)

[a]Color code: dark green, ideal for use in analogies; light green, acceptable for use in analogies; yellow, not ideal for use in analogies.

TABLE 4. Categorization and potential impact of analogies by scale (only one set of codes per assignment was possible)[a]

Scale: Target science concept	Scale: Analogue	Percent (no. of assignments)	Participant examples
Bridge analogies: Ideal analogies connecting abstract concepts from the microscopic, macroscopic, or methodological realms to everyday objects or experiences in the mesocosm; they are highly accessible to students.			
Microscopic	Mesoscopic	44 (33 of 75)	"DNA mutations are like mistakes in a cooking recipe." (21S14) "Antibiotic resistance vs. tolerance is like suntanning vs. skin color." (19S5)
Macroscopic	Mesoscopic	15 (11 of 75)	"Natural selection's selective pressure is like getting dressed." (20S9) "Ecological succession is like the timeline of a big party." (21S5)
Methodological	Mesoscopic	24 (18 of 75)	"Incidence and prevalence of diseases are like water flow in a bathtub." (18F9) "Functions in computer programming are like cooking." (19F3)
Stationary analogies: Analogies that do not cross from one realm of scale to another; depending on the desired learning outcome, these analogies may be problematic for learners.			
Microscopic	(Functionally) microscopic[b]	5 (4 of 75)	"Hormone function is like sending an SMS." (18F2) "Bacteria persistence is like a smartphone going into sleep mode." (19F5) "A plasmid is a USB stick." (19F13)
Mesoscopic[c]	Mesoscopic	5 (4 of 75)	"Niche complementarity hypothesis is like compromising with housemates." (21S1) "Commensalism vs. mutualism is like marriage vs. hitchhiking." (21S2)
Flyover analogies: Analogies that compare a microscopic science concept to a macroscopic analogue, flying over the middle ground mesocosm; learners reap little benefit from embodiment.			
Microscopic	Macroscopic	4 (3 of 75)	"Atomic orbitals are like clouds." (18F11) "Stem cell division is like the development of identical twins until adulthood." (18F12)

[a]Color code: green, optimal analogy; yellow, suboptimal analogy.
[b]These (functionally) microscopic analogues seem mesoscopic, but the learning outcomes participants planned to achieve with these analogies are microscopic in scale (e.g., equivalent to understanding the microcircuitry of how SMSs, smartphones, or USB sticks work).
[c]Also considered to be near analogies (see *Far Analogies Safeguard against Overinterpretation and Misconceptions*).

- Bridge analogies (83% of assignments) have mesoscopic elements in their analogues mapped to microscopic, macroscopic, or theoretical elements in their target science concepts. For example, the analogy "DNA mutations are like mistakes in a cooking recipe" (21S14), compares microscopic molecular changes to DNA to the mesoscopic experience of cooking and finding a mistake in the recipe. According to embodied cognition, this combination should enable students to use their own personal understanding of the directly perceptible, experienceable analogue to bridge/gain access to the understanding the abstract scientific content.
- Stationary analogies (10% of assignments) contained mappings in which the analogue and science concept came from the same scale. We called these "stationary analogies" as they did not involve the mapping of relationships that move across scales. For example, the analogy "Niche complementarity hypothesis is like compromising with housemates" relates two mesoscopic phenomena—how organisms occupy and function in their surroundings (assuming those organisms are not microscopic) and how humans function in a housemate situation. Problematic here is that the components of the analogy are quite similar (i.e., a near analogy). This makes the analogy prone to overinterpretation or seeing similarities beyond what is appropriate or true. In other examples, stationary analogies can be additionally nonoptimal for learning due to their lack of connection to the mesocosm.
- Flyover analogies (4% of assignments) skipped the mesocosm and mapped from the microscopic to the macroscopic scales. For example, in the analogy "Stem cell division is like the development of identical twins until adulthood," the microscopic details of how cells divide is related to the process of human growth, which is macroscopic due to the length of time it requires. Flyover analogies like this one are likely to produce misunderstanding, as both realms are not directly perceptible, so flyover analogies skip the power of the mesocosm.

Degree and Impact of Shared Features in the Analogies

To have a sense of how participants' choices of target concepts and analogues align with what is known about the risk of overinterpretation of an analogy, we looked at the indicator of similarity between the science concept and analogue known as "nearness" and "farness," which we described in the *Introduction*. Nearly two-thirds (61%) of participant analogies were categorized as far (see Table 5), which we defined as an analogy in which the analogue and science concepts come from different

TABLE 5. Degree of shared features between analogue and target concept (only one code per assignment was possible)[a]

	Categorization of the assignment: % (no. of assignments)	Coding criteria	Participant examples and explanation of categorization
Most shared features <- - - - - - - - -> Least shared features	Far analogy 61 (46 of 75)	Analogue and target concept have obscure similarities and differences; seem more incongruous; and come from different/unsimilar systems.	"Incidence and prevalence in epidemiology are like the water flow in a bathtub." (18F9) This is a far analogy, as it brings together an analogue and target concept with non-obvious similarities and significant differences. Typical of a far analogy, the comparison is initially obscure and requires students to find the underlying functional or causal relationships that make the comparison meaningful.
	Near analogy 16 (12 of 75)	Analogue and target concept have readily apparent surface and structural similarities and differences; they come from similar systems.	"Chemiosmosis is like a hydroelectric dam." (19S12) This is a near analogy, as it brings together structures and processes that have more differences, especially functional, than an example would. Typical of a near analogy, the surface and structural similarities are clear—both components involve a similar system of physical restraint of material leading to a buildup of their quantity.
	Example (not an analogy) 23 (17 of 75)	Comparison contains clear structural and functional similarities and few or no differences	"Diffusion across a cell membrane is like the spreading of tea in a cup." (19F4) Here the participant made a good connection to everyday life, but this comparison requires no analogical thinking. It describes two examples of the same physical process with no salient differences, especially in function.

[a]Color code: dark green, optimal analogy; light green, useful for teaching, but not an analogy; yellow, suboptimal analogy.

or unsimilar systems (e.g., cell structure and urban structure or baseball and mathematics) with few obvious surface or structural similarities (Halpern *et al.*, 1990). We consider this a good result for novice teachers. Sixteen percent of analogies were near, that is, analogies in which the analogue and science concept come from the same or very similar systems (e.g., plant immune system and human immune system or baseball and basketball) and have readily apparent surface and structural similarities (Halpern *et al.*, 1990).

We found it necessary to include an additional category for the 23% of assignments in which the degree of similarity between the analogue and target science concept was so high that there was little to no dissimilarity. We considered these cases to be "examples," not analogies, based on the structure-mapping theory of Gentner (1983), which describes "literal similarities" as distinct from analogies due to the near-complete overlap between the analogue and target concept. Gentner suggests literal similarities fulfill a different role in thinking than do analogies, as their high degrees of overlap distracts from the ability to focus in on relational or causal comparisons (see Table 5).

For clarification, we will refer again to our model analogy: "Mass spectrometry is like the time needed to walk home from the grocery store." We have already pointed out the high level of embodiment in this analogy, which means the analogue is familiar and accessible. Now we highlight another layer of good design, which is the analogy's far nature. The analogue of a human walking has few obvious superficial or other similarities to mass spectrometry, and the two clearly come from different systems—human behavior versus technical research methodology. The lack of clear surface or structural relationships between the target concept and analogue means students would have to process this analogy more deeply in order to find the similarities in its underlying functional relationships. In contrast to a near analogy, this one has a lower likelihood that students would map too many similarities and therefore overinterpret it (Halpern *et al.*, 1990).

Deconstructing the Analogy by Identifying Similarities and Differences

An important aspect of teaching with analogies is identifying where an analogy breaks down. Therefore, we asked participants to identify not only similarities in their analogies, but also differences. In 75 assignments, participants mapped 355 similarities between the science concept and analogue ("likes") and 149 differences between the science concept and analogue, or ways in which the analogy no longer works ("dislikes"). The difference between these two values is likely explained by the fact that many of the similarities were the means of explaining the setup of the analogy, for example: "Functions are the recipes, arguments are the ingredients, returns are the finished dishes, the computer is a cook" (19F3). We found participants wrote a lot of text in this step of the assignment, and they reported finding it difficult. Table 6 shows directly quoted samples of participants' work to give an idea of the typical length and level of detail of the mapping work in the assignments.

Unexpected Prevalence of Anthropomorphism

While analyzing the mappings, we noticed a large number of statements in nearly a third of assignments contained anthropomorphic logic. We considered this a surprising finding, given our course participants' high apparent levels of content knowledge and expertise in the life sciences as PhD students. We now know that other studies have also found a high prevalence of this kind of logic beyond the school and bachelor levels. For example, Betz *et al.* (2019) found *instructor*

TABLE 6. Examples of directly quoted participant mapping of analogy likes and dislikes

	Likes: similarities between the science concept and analogue; where the analogy works	Dislikes: differences between the science concept and analogue; where the analogy breaks down
"The light-dependent reaction is like a water channel with pumps." (21S12)	• The PS II and PS I are like water pumps. • Electrons are like water in the channel. • Light is like power-driven pumps. • The cytochrome complex and ATP synthase are like waterwheels providing mechanical power.	• Although this analogy is effective for understanding, it compromises some accuracy of scientific notions. • First, the light-dependent reaction is at the nanometer to micrometer scale, but the water channel is at the meter scale. • The reaction within a cell produces oxygen and converts light energy to chemical energy, but the water channel does not. • The pigments in PS II and PS I emit fluorescence back to the sky, but water pumps only consume energy.
"Mass-spectrometry is like the time needed to walk home from the grocery store." (21S8; our model analogy)	• The molecule's mass is the weight of your groceries. • The distance the ions fly in the magnetic field is the way home. • The molecule's charge is your motivation to reach home. • The time you needed to carry your groceries is the time of flight through the magnetic field over a defined distance home from the store.	• In the mass spectrometer, the molecules fly, and in the analogy, you carry them (i.e., the groceries). Assuming you are always the same weight, this can be seen as a constant and ignored from the example. • Motivation can not only be positive or negative but also neutral; ions are molecules with a charge (+ or –), and for the method to work, any compound that wants to be measured gets ionized just before time of flight assessment by an ion source. • Your speed home depends not only on the weight of you and your groceries and your motivation, but also on your physical state and whether environmental factors hold you back/speed you up (e.g., you meet a friend on your way home and stop to chat or someone you know drives by and gives you a lift); the speed of a molecule with the same mass and charge is always the same over the same distance in the same magnetic field.

language commonly contained anthropomorphic, teleological, and essentialist thinking. Here are two examples of anthropomorphism (anthropomorphism is underlined within the participant quote):

> Protein degradation is like recycling: "Everyday products are used for a certain time. When they stop being useful, they become garbage. Proteins are produced with the intention to fulfill onespecific goal. Once this goal has been met, the protein is degraded." (19F7)

> Parasitic plant fungus is like shoplifting in a grocery store: "The effector protein/shoplifter enters the cell/grocery store and tries to steal nutrients/food from there without being noticed. … However, there is the case when there is an assistant of the shoplifter/suppressor protein that can create a diversion and thus help the shoplifter acquire the nutrients/food." (19S14)

We also noticed that the anthropomorphism was rarely addressed by the participants when mapping the dislikes of their analogies. In fact, only 13 of a total of 504 mappings (in 12 of the 75 assignments) showed an awareness by the participant that anthropomorphism was present. Here are two examples of awareness:

> Hysteresis and alternative stable states (in population ecology) are like the effort people need to change their lifestyle—unlike: "The ecology case depends on an external force, whereas the lifestyle depends more on internal force to change." (19F8)

> Carcinogenesis is like abandoning a garden—unlike: "There is no central governor regulating carcinogenesis in the body like a gardener taking care of the garden. We cannot actively influence cell misgrowth in our body." (21S3)

Participants' Reflections on Teaching with Analogies

As participants were only planning analogies and not actually teaching with them (at least at the time of completing the assignment), we deviated from the reflection prompts in the FAR guide. We asked the following two questions instead: 1) How is the method of teaching with analogies presented in the course different from how you have taught before or how you were taught as a student? 2) How would you know if your analogy will lead to a good learning outcome for your own students? The first question was designed to elicit information about participants' learning in our course and their perception of the fit of our analogy tool for a higher education audience. The second question was designed to keep participants' focus on their students and is mentioned here only as an example of TSU's focus on PCK.

Participant answers to the first question focused upon their own experiences as students, their limited experiences as teachers, and/or their ideas for future teaching. Many recalled general, positive student experiences with analogies ($n = 38$), for example, that the best courses used them, or that they made content easier to follow. Others ($n = 26$) recalled negative, more specific experiences—that they did not receive thorough guidance through an analogy, leading to more confusion than help; that there was insufficient use of analogies—they were only used for superficial aspects of the content but were never complex analogies nor were they deconstructed during discussion.

Many reflections ($n = 12$) contained ideas about teaching practices described as new or different from what participants had known or experienced before. We cautiously interpret these as evidence of learning in TSU. These statements focused on the importance of teaching systematically with analogies, especially of having students actively analyze likes and dislikes:

> "I like to teach by analogies. But it is the first time I consider in detail the analogy so that it could be familiar for the students and it is the first time I highlight likes and unlikes in a systematic manner." (19F2)

of planning them in advance:

> "I often try use analogies when I teach, but I have not really prepared them in this manner. Typically they are small analogies about a very particular concept that I spontaneously use." (19F6)

and of ensuring student familiarity with the analogue:

> "I usually try to teach with analogies, but I actually never thought that the analogy must be very, very easy to understand and familiar to all the students, otherwise it does not make sense to use it." (19F7)

Reflecting more generally, participants made positive statements about the roles analogies can have in learning: that they can aid and speed students' comprehension ($n = 12$), aid recall ($n = 5$), and make complicated, abstract subjects more approachable ($n = 5$). These statements mirror the content of the module's instructional videos and handouts, but we cannot say for sure that participants' ideas come directly from our course.

DISCUSSION

In this paper we analyzed 75 teaching analogy assignments produced by GTAs participating in an introductory university science pedagogy course, TSU. The course's analogy module paired a structured tool for designing teaching analogies, the FAR guide, developed for K–12 school teaching, with the theory of embodied cognition, that learning takes place also through our bodily and cultural interactions with the world around us. We wanted to know how useful and effective our course's guidance was for higher education and for helping life science instructors develop analogies to use in their teaching. This *Discussion* focuses on those findings from our analysis that indicate strengths and weaknesses of our course. Then, in the *Implications and Conclusions*, we suggest strategies for teaching with analogies that highlight these strengths and address the weaknesses.

A Structured Approach Can Help Ensure Good Analogy Design

At the most basic level, we can see that course participants were able to follow the TSU analogy module and its use of the FAR guide to systematically design and reflect upon analogies for their teaching. We could also see that participants' analogies mostly held up to recommendations from prior research on effective analogies: Nearly all science concepts chosen as the target concepts were outside the mesocosm (i.e., abstract; Table 2), 69% of analogies contained a high or medium degree of embodiment (i.e., were experience based; Table 3), 83% of analogies made connections between the abstract and the everyday (i.e., bridge analogies; Table 4), and 61% of analogies were categorized as far analogies (Table 5). It is important to recall the special audience of TSU in order to understand the significance of these results. TSU participants are life scientists who aspire to research excellence. They are novice teachers with nearly no prior training. Nevertheless, they produced analogies well aligned with the research, which we suggest is indicative of the development of PCK, as there is wide agreement that effective use of analogies is an important part of teachers' PCK (Shulman, 1986; Dagher, 1995; Gess-Newsome, 1999).

"Scale" Resonates More Than "Embodiment" to Assess Difficulty of Science Concept

When describing the science concept for their analogies, participants chose predominantly from the microcosm, macrocosm, and methodological realms (only 9% were mesoscopic). This is a meaningful result, as novice teachers can struggle to estimate what will be difficult for students and to plan for topic-specific difficulties, both of which are skills associated with PCK (Auerbach *et al.,* 2018). We believe our use of the notion of scale (micro/meso/macrocosm) to give our future life scientist participants familiar and concrete criteria with which judge a science concept's difficulty and abstractness was key to this good result. However, despite the fact that a growing number of researchers and educators have adopted embodied cognition frameworks in their teaching (Kolovou, 2022), very few TSU assignments included any mention of embodied cognition. It seems participants connected more with our means of operationalizing embodiment using scale, that concepts outside the realm of the mesocosm tend to be more difficult to understand.

Mesoscopic, Embodied Analogues Safeguard against Analogy Design Problems

Eighty-three percent of participant analogies made some connection between non-mesoscopic science concepts and mesoscopic analogues (i.e., "bridge analogies" in Table 4). Those which did not use mesoscopic analogues were considered to have design problems that could potentially complicate learning. Take, for example, the "stationary analogies" involving a microscopic science concept and what we called a "functionally microscopic" analogue in Table 4. These analogues were technical objects such as a copy machine, smartphone, camera, or USB stick, which at first glance seem to logically belong to the mesocosm. The problem, however, is that the intended learning outcomes for the analogies made clear that students would need to understand the inner workings of the objects—how toners combine in sequence to produce color copies, how and why smartphones go into sleep mode, how cameras use attenuation to produce images—and we consider this to be specialist, non-everyday knowledge involving microscopic, nonvisible processes. Analogies that refer to technical everyday objects seem catchy and easy to understand at first glance. But because they only allow the surface structures of a concept to be understood, they can also turn out to be a "seductive trap," creating only an "illusion of understanding." In these cases, students may think they understood a concept deeply but they only scratched its surface.

What is missing in the design choice of these problematic analogues is the element of embodiment—a student usually does not experience the inner workings of a camera. Analogies without connections to embodied conceptions can leave students with scientifically inadequate conceptions and problems transferring meaning from the analogue to the scientific phenomenon (Harrison and De Jong, 2005). In sum, if the desired student learning outcome only required a knowledge of the overall *effect* or *role* of the technical object, then these analogies would likely pose no problem; but the learning goal our participants set for the lesson required a knowledge of the microscopic *processes* taking place *within* the technical object in order to map to and understand the science concept. In this case, everyday familiarity of the analogue was insufficient. Generally, the more process-based the science concept is, as in this example, the more careful one needs to be with embodiment of the analogue (Niebert *et al.*, 2012).

Far Analogies Safeguard against Overinterpretation and Misconceptions

A second analogy design issue we found was that some analogues were too near to the science concept. This could occur when the components of the analogy came from similar systems, for example, bacterial conjugation is like sexual reproduction (18F3) or when they occurred at the same scale, for example, reproducing a research study (mesoscopic) is like cooking with a recipe (also mesoscopic; 18F7). In these cases (i.e., "near analogies" in Table 5; as well as mesoscopic-to-mesoscopic "stationary analogies" in Table 4), there is a clear parallel structure between superficial features of the analogue and those of the science concept, and as a result, students can easily overgeneralize about the similarities in the analogy to the point of misconception—students could assume bacteria have different genders or that conjugation is for the purpose of reproduction (which it is not). Or students could miss important functional differences, such as the role of reproducing research in ensuring scientific integrity—something that has no parallel in cooking.

In their ability to promote both understanding and recall, near analogies are less effective than far analogies (Halpern *et al.*, 1990). This is a slightly counterintuitive notion—that analogies with *less* similarity are *more* effective. If we look at a participant example of a far analogy, incidence and prevalence are like the water flow in a bathtub (18F9), we can start to understand their seeming superiority. In this case, the analogy's embodied action—filling and draining a bathtub—and its target concept in disease epidemiology have little obvious in common. Students therefore have to engage deeply with the analogy to find the similarities in underlying function or causation. This deep engagement is believed to underlie the strength of analogies as instructional tools (Hammadou, 2000). Sixty-one percent of TSU participants' analogies were deemed far analogies, which we feel is a good result for beginners in a pedagogy course. Nevertheless, further guidance on the shortcoming of near analogies and how to counteract them with active student mapping of the analogy (especially dislikes) would be an important addition to our course.

Anthropomorphic Reasoning

A third issue we noticed was the presence of anthropomorphic logic in a large proportion (32%) of the participants' analogies. This anthropomorphism would not be a problem *if* it was identified as a dislike and *if* participants showed awareness of the need to discuss how parallel intentional behavior would not be possible in the related science concept. However, in the 504 total mappings done in the 75 assignments, only 13 showed an awareness of anthropomorphism.

Anthropomorphism is a thinking pattern in which elements of human reasoning such as intentionality or goal-directedness are attributed to nonhuman organisms or inanimate objects that are incapable of such thought processes as far as we know (Tamir and Zohar, 1991). It is a form of intuitive biological thinking known as a cognitive construal, similar to anthropic (anthropomorphic + anthropocentric), teleological, and essentialist thinking (Coley and Tanner, 2015; Betz *et al.*, 2019). If we look at participant 19S14's analogy about parasitic fungi, s/he states: "The effector protein/shoplifter enters the cell/grocery store and *tries to steal nutrients/food from there without being noticed*.… However, there is the case when there is an assistant of the shoplifter/suppressor protein that can *create a diversion* and thus help the shoplifter acquire the nutrients/food." Trying to evade notice or create a diversion are goal-directed behaviors impossible for a nonliving protein. Similarly participant 19F7 suggested goal-directed, purposeful creation of proteins by cells: "Proteins are produced *with the intention to fulfill one specific goal. Once this goal has been met, the protein is degraded.*" This statement reinforces language frequently used in explanations of living systems that implies entities such as nuclei or ribosomes act with intention instead of simply reacting. Perhaps such thinking is less problematic in everyday communication or at the K–12 school level where anthropomorphism might enliven, humanize, and make more accessible the mystery and surprise of scientific discovery (Lemke, 1990), but we suggest it must be addressed when educating for the expert-level disciplinary thinking characteristic of higher education. In formal communication, scientists consider anthropomorphic explanations to be unscientific, often teleological, to have problems with causality, and to "lead (scientists) to include unevidenced and unnecessary external forces in their explanations" (McGellin *et al.*, 2021, p. 622). Furthermore, anthropomorphic logic is often grouped with personification and sensationalism as communication practices scientists avoid in the name of serious and correct scientific discourse (Taber and Watts, 1996).

We suspect that the presence of anthropomorphism is a consequence of our emphasis on mesoscopic, experience-based analogues, which tend to involve humans and therefore the possibility of intentional actions. This fits with the work of Coley and Tanner, who found anthropocentrism (which they define similarly to our definition of anthropomorphism—i.e., inclusive of reasoning about unfamiliar biological species or processes by analogy to humans) can lead to an "overattribution of human (or animal) functions to dissimilar organisms (e.g., plants), or personification of physiological processes" (2015, p. 5). Perhaps, then, anthropomorphism in the analogies is acting as an acceptable temporary scaffolding that gives students accessibility to the science concept. It is then critical to remove the scaffolding as student learning progresses by specifically identifying the anthropomorphism in the analogy and discussing its incompatibility with an accurate scientific understanding of the target science concept. There is support for this strategy that finds anthropomorphic language diminishes over time as student explanations shift to more accurate, mechanistic forms (Taber and Watts, 1996; Betz *et al.*, 2019).

Analogies Should Be Well Planned and Thoroughly Discussed

Our analysis of participants' reflections at the end of the assignment showed further interesting results in terms of their understanding of analogies as a pedagogical tool. Participants noted many benefits to teaching with analogies, such as facilitating connections to real life and making abstract concepts more accessible. And crucially, they no longer thought of analogies as spontaneous tools that can be used without careful consideration of familiarity and comprehensibility to students. The revelations about forethought perhaps stem from the fact that the entire first stage of the FAR guide happens before class and details significant planning and careful consideration about student interaction with the analogy. This was an intentional design choice by the FAR guide authors, intended to increase the likelihood that in-class time on the analogy would be spent in active discussion of the analogy's strengths and weaknesses (likes and dislikes; Treagust *et al.*, 1998).

At a more sophisticated level, the structured, systematic nature of the FAR guide and its emphasis on interactions with students seems to have impacted how participants conceptualized the overall act and sequence of teaching with analogies. For one, the tone and terminology used in the instructional steps of the action stage all depict active interactions with students (e.g., "check," "discuss"). This is certainly not the norm in higher education, where the predominant mode of teaching is still lecturing and a one-way transmission of information (e.g., Wieman, 2017). And the specific prompt to evaluate where the analogy fails (i.e., the dislikes—where the analogue no longer maps to the science concept) and to do so actively with students during teaching seems to have made a particularly strong impression on participants, as evidenced by its common presence in their reflection statements. Most striking was the common reflection that few had ever seen or considered this important step. This finding echoes the work of Venville and Treagust (2002), who found that some popular analogies are used ineffectively by teachers, because they are only used to point out a quick similarity and no attention is paid to where the analogy does not work, leaving learners with knowledge that can easily create misconceptions. Here, we see the value of a structured tool for analogy design most clearly. Through its straightforward, detailed prompts, participants were guided to teach with analogies in a different manner than most had experienced as students. When we combine the tool's instructions of *what* to do with the theory and research evidence presented in the TSU analogy module on *why* to teach in this manner, there is a chance to break the higher education cycle of instructors teaching as they were taught, a "socialization-based approach [that] is resistant to change and improvement" (Teräs, 2016, p. 260).

LIMITATIONS

The main limitation of this study is that participants' analogies and plans for implementing them were developed in the context of an assignment meant to facilitate transfer of general understanding about analogies (PK) to one's specific teaching subject and context (PCK). We suspect few, if any, participants had the chance to teach with the specific analogies they described in our course. We are therefore cautious about drawing any conclusions about the impact of TSU or of our structured analogy design guide on actual teaching practice or on the development of participants' PCK. Furthermore, we are cautious in making claims about the FAR guide itself, as our analysis is limited to the "F" for focus phase (preclass planning). We do not examine the "A" or action phase (in class implementation of analogy) or "R" or reflection phase (postclass evaluation of analogy suitability and effectiveness). Finally, as the use of analogies is very common, we are aware that a wide range of prior knowledge and experience with analogies exists among our participants. We are therefore cautious to draw conclusions about participants' learning in TSU, except in the cases where participants explicitly attribute changes in beliefs or practices to the course.

IMPLICATIONS AND CONCLUSIONS

According to the theory of embodied cognition, analogies are integral to our understanding. And while affording direct experience in science teaching as Niebert and Gropengiesser (2015) propose may be the first, best option, this can be a time-consuming endeavor and particularly challenging in the high-enrollment classes typical of university life science. Implementing and deconstructing analogies is a very good option as well, and based on our results and interpretations, we conclude that a structured tool like the FAR guide is useful and effective for future life science instructors to develop and reflect upon using analogies in their university teaching. Based upon the strengths and weaknesses we found in our analysis of participants' analogies—where the tool was sufficient versus where it could be modified for the university level, we propose the following implications for teaching with analogies in higher education:

PLAN: Thoroughly plan analogies and how to teach with them in advance.

- Aim for far analogies that have fewer surface or structural similarities between the analogue and science concept. Students must think deeply to find the likes and dislikes of these analogies, and this reduces the risk of overinterpretation/overgeneralization of the analogical relationship.

BRIDGE: Use mesoscopic, experience-based analogues to best ensure student access to the analogy.

- Analogues that are familiar to your students, and preferably everyday experiences they could simply remember, are ideal in analogies, as they have a low cognitive load and allow students to focus on mapping to the target science concept.

INTERACT: Prioritize active student discussion of the analogy's strengths and weaknesses, including discussion of anthropomorphic logic.

- Active student discussion of the analogy safeguards against overinterpretation of similarities between the analogue and the science concept. Leaving out this critical step can lead to undesired learning outcomes.
- Help students identify and reflect upon when anthropomorphism is suitable and unsuitable for explaining concepts.

Overall, specific instruction on the effective use of analogies was an important and deeply appreciated component of TSU noted by the course participants. Many of our young life scientist participants had never experienced this kind of teaching themselves as students or GTAs and reacted very positively to the role analogies could play in their future teaching. The FAR guide, a structured approach to planning and teaching with analogies from the K–12 school setting, has been shown to be useful and appropriate for university-level science education. Its specific prompts ensure consideration of student prior knowledge, interests, and experiences and call for more active student involvement and critical thinking during instruction than is typical of university lecturing. It is important to remember that the FAR guide was designed for K–12 school classrooms and assumes a smaller class size and greater opportunity for interactivity than is the norm in most university lectures. However, there is a growing awareness of the need to incorporate small-group work in traditional lecture courses for more student-centered learning (e.g., Bailey *et al.*, 2012).

ACKNOWLEDGMENTS

This research was supported by the University of Zurich. We thank Dr. Petra Breitenmoser and Dr. Sandra Lang for their vital help with data analysis and coding. Petra Breitenmoser was the third coder for the deductive qualitative content analysis. Sandra Lang was the fourth coder and was involved in the inductive qualitative content analysis. We also thank the editor and reviewers of the paper for their thorough and insightful comments on the paper. The coding manual is available online.

REFERENCES

Auerbach, A. J., Higgins, M., Brickman, P., & Andrews, T. C. (2018). Teacher knowledge for active-learning instruction: Expert-novice comparison reveals difference. *CBE—Life Sciences Education*, *18*(4), ar12. https://doi.org/10.1187/cbe.19-01-0010

Bailey, C. P., Minderhout, V., & Loertscher, J. (2012). Learning transferable skills in large lecture halls: Implementing a POGIL approach in biochemistry. *Biochemistry and Molecular Biology Education*, *40*(1), 1–7. https://doi.org/10.1002/bmb.20556

Betz, N., Leffers, J. S., Dahlgaard Thor, E. E., Fux, M., de Nesnera, K., Tanner, K. D., & Coley, J. D. (2019). Cognitive construal-consistent instructor language in the undergraduate biology classroom. *CBE—Life Sciences Education*, *18*(4), 1–16. https://doi.org/10.1187/cbe.19-04-0076

Beynon, J. H., & Brown, L. (2023, February 10). Mass spectrometry. *Britannica*. Retrieved February 24, 2023, from www.britannica.com/science/mass-spectrometry

Carlson, J., & Daehler, K. R. (2019). The refined consensus model of pedagogical content knowledge in science education. In Hume, A., Cooper, R., & Borowski, A. (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 77–92). Singapore: Springer. https://doi.org/10.1007/978-981-13-5898-2_2

Coe, R., Aloisi, C., Higgins, S., & Major, L. E. (2014). *What makes great teaching? Review of the underpinning research (Project report)*. London, England: Sutton Trust.

Coley, J. D., & Tanner, K. (2015). Relations between intuitive biological thinking and biological misconceptions in biology majors and nonmajors. *CBE—Life Sciences Education*, *14*(1), ar8. https://doi.org/10.1187/cbe.14-06-0094

Curtis, R. V., & Reigeluth, C. M. (1984). The use of analogies in written text. *Instructional Science*, *13*, 99–117. https://doi.org/10.1007/BF00052380

Cvenic, K. M., Ivanjek, L., Planinic, M., Jelicic, K., Susac, A., & Hopf, M. (2021). Analyzing high school students' reasoning about polarization of light. *Physical Review Physics Education Research*, *17*(010136), 1–16. http://doi.org/10.1103/PhysRevPhysEducRes.17.010136

Dagher, Z. R. (1995). Review of studies on the effectiveness of instructional analogies in science education. *Science Education*, *79*(3), 295–312. https://doi.org/10.1002/sce.3730790305

Duit, R. (1991). On the role of analogies and metaphors in learning science. *Science Education*, *75*, 649–672.

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science*, *7*(2), 155–170. https://doi.org/10.1016/S0364-0213(83)80009-3

Gess-Newsome, J. (1999). Pedagogical content knowledge: An introduction and orientation. In Gess-Newsome, J., & Lederman, N. G. (Eds.), *Examining pedagogical knowledge: The construct and its implication for science education* (pp. 3–17). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/0-306-47217-1

Glynn, S. M. (2008). Making science concepts meaningful to students: Teaching with analogies. In Mikelskis-Seifert, S., Ringelband, U., & Brückmann, M. (Eds.), *Four decades of research in science education: From curriculum development to quality improvement* (pp. 113–125). Münster, Germany: Waxmann.

Glynn, S. M., & Takahashi, T. (1998). Learning from analogy-enhanced science text. *Journal of Research in Science Teaching*, *35*(10), 1129–1149.

Halpern, D. F., Hansen, C., & Riefer, D. (1990). Analogies as aid to understanding and memory. *Journal of Educational Psychology*, *82*(2), 298–305.

Hammadou, J. (2000). The impact of analog and content knowledge on reading comprehension: What helps, what hurts. *Modern Language Journal*, *84*(1), 38–50. https://doi.org/10.1111/0026-7902.00051

Harrison, A. G., & Coll, R. K. (Eds.) (2008). *Using analogies in middle and secondary science classrooms: The FAR guide—an interesting way to teach with analogies*. Thousand Oaks, CA: Corwin Press.

Harrison, A. G., & De Jong, O. (2005). Exploring the use of multiple analogical models when teaching and learning chemical equilibrium. *Journal of Research in Science Teaching*, *42*(10), 1135–1159.

Harrison, A. G., & Treagust, D. F. (2006). Teaching and learning with analogies: Friend or foe? In Aubusson, P. J., Harrison, A. G., & Ritchie, S. M. (Eds.), *Metaphor and analogy in science education* (pp. 11–24). Dordrecht, Netherlands: Springer.

Hattie, J. (2009). *Visible learning: A synthesis of over 800 meta-analyses relating to achievement*. Oxford, UK: Routledge.

Holyoak, K.J. (2005). Analogy. In Holyoak, K. J., & Morrison R. G. (Eds.), *The Cambridge handbook of thinking and reasoning* (pp. 117–142). New York, NY: Cambridge University Press.

Johnson, A. C. (2007). Unintended consequences: How science professors discourage women of color. *Science Education*, *91*(5), 805–821. https://doi.org/10.1002/sce.20208

Johnson, M. (2015). Embodied understanding. *Frontiers in Psychology*, *6*(875), 1–8. https://doi.org/10.3389/fpsyg.2015.00875

Kolovou, M. (2022). In search of assessment shifts in embodied learning science research: A review. *Journal of Science Education and Technology*, *31*, 246–257. https://doi.org/10.1007/s10956-021-09952-x

Krepf, M., Plöger, W., Scholl, D., & Seifert, A. (2018). Pedagogical content knowledge of experts and novices—What knowledge do they activate when analyzing science lessons? *Journal of Research in Science Teaching*, *55*(1), 44–67. https://doi.org/10.1002/tea.21410

Lakoff, G. (2012). Explaining embodied cognition results. *Topics in Cognitive Science*, *4*, 773–785. https://doi.org/10.1111/j.1756-8765.2012.01222.x

Lakoff, G., & Johnson, M. (2008). *Metaphors we live by.* Chicago: University of Chicago Press.

Lakoff, G., & Núñez, R. (2000). *Where mathematics comes from*. New York, NY: Basic Books.

Lee, E., & Luft, J. A. (2008). Experienced secondary science teachers' representation of pedagogical content knowledge. *International Journal of Science Education*, *30*, 1343–1363.

Lemke, J. L. (1990). *Talking science: Language, learning and values.* Norwood, NJ: Ablex.

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry.* London, England: Sage.

Mayring, P. (2002). Qualitative content analysis—research instrument or mode of interpretation? In Kiegelmann, M. (Ed.), *The role of the researcher in qualitative psychology* (pp. 139–148). Tübingen, Germany: Huber.

Mayring, P. (2014). *Qualitative content analysis: Theoretical foundation, basic procedures and software solution.* Klagenfurt. Retrieved July 5, 2022, from https://nbn-resolving.org/urn:nBn:dE:0168-ssoar-395173

McGellin, R. T. L., Grand, A., & Sullivan, M. (2021). Stop avoiding the inevitable: The effects of anthropomorphism in science writing for non-experts. *Public Understanding of Science*, *30*(5), 621–640. https://doi.org/10.1177/0963662521991732

Neumann, K., Kind, V., & Harms, U. (2019). Probing the amalgam: The relationship between science teachers' content, pedagogical and pedagogical content knowledge. *International Journal of Science Education*, *41*(7), 847–861. https://doi.org/10.1080/09500693.2018.1497217

Niebert, K., & Gropengiesser, H. (2015). Understanding starts in the mesocosm: Conceptual metaphor as a framework for external representations in science teaching. *International Journal of Science Education*, *37*(5–6), 903–933. https://doi.org/10.1080/09500693.2015.1025310

Niebert, K., Marsch, S., & Treagust, D. F. (2012). Understanding needs embodiment: A theory-guided reanalysis of the role of metaphors and analogies in understanding science. *Science Education*, *96*(5), 849–877. https://doi.org/10.1002/sce.21026

Petchey, S., & Niebert, K. (2021). Educational reconstruction as a model for designing university science teaching at university: Insights from a massive open online course for early career science instructors. *Herausforderung Lehrer*innenbildung Zeitschrift zur Konzeption, Gestaltung und Diskussion*, *4*(2), 193–212. https://doi.org/10.11576/hlz-2699

Richland, L. E., & Simms, N. (2015). Analogy, higher order thinking, and education. *Wiley Interdisciplinary Reviews: Cognitive Science*, *6*(2), 177–192. https://doi.org/10.1002/wcs.1336

Seymour, E., & Hunter, A-B.((2019). *Talking about leaving revisited: Persistence, relocation, and loss in undergraduate STEM education.* Cham, Switzerland: Springer.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher*, *15*, 4–14. https://doi.org/10.3102/0013189X015002004

Smith, C. R., & Delgado, C. (2021). Developing a model of graduate teaching assistant teacher efficacy: How do high and low teacher efficacy teaching assistants compare? *CBE—Life Sciences Education*, *20*(1), 1–10. https://doi.org/10.1187/cbe.20-05-0096

Tamir, P., & Zohar, A. (1991). Anthropomorphism and teleology in reasoning about biological phenomena. *Science Education*, *75*(1), 57–67.

Taber, K. S., & Watts, M. (1996). The secret life of the chemical bond: Students' anthropomorphic and animistic references to bonding. *International Journal of Science Education*, *18*(5), 557–568, https://doi.org/10.1080/0950069960180505

Teräs, H. (2016). Collaborative online professional development for teachers in higher education. *Professional Development in Education*, *42*(2), 258–275. https://doi.org/10.1080/19415257.2014.961094

Treagust, D. F., Duit, R., Joslin, P., & Lindauer, I. (1992). Science teachers' use of analogies: Observations from classroom practice. *International Journal of Science Education*, *14*(4), 413–422.

Treagust, D. F., Harrison, A. G., & Venville, G. J. (1996). Using an analogical teaching approach to engender conceptual change. *International Journal of Science Education*, *18*(2), 213–229. https://doi.org/10.1080/0950069960180206

Treagust, D. F., Harrison, A. G., & Venville, G. J. (1998). Teaching science effectively with analogies: An approach for preservice and inservice teacher education. *Journal of Science Teacher Education*, *9*(2), 85–101. https://doi.org/10.1023/A:1009423030880

University of Zurich. (2014). *Ethik in der Forschung: Checklist to self-assess studies concerning their ethical safety.* Retrieved July 5, 2022, from www.phil.uzh.ch/dam/jcr:7Ae73448-941f-4d26-b0f5-96859fa1cabd/141131_PhF_Ethics_Committee_Checklist_Self-Assessment.docx

van Driel, J., Verloop, N., & de Voss, W. (1998). Developing science teachers' pedagogical content knowledge. *Journal of Research in Science Teaching*, *35*, 673–695.

Venville, G. J. (2008). The Focus-Action-Reflection (FAR) guide—Science teaching analogies. In Harrison, A. G., & Coll, R. K. (Eds.), *Using analogies in middle and secondary science classrooms: The FAR guide—An interesting way to teach with analogies* (pp. 22–31). Thousand Oaks, CA: Corwin Press.

Venville, G. J., & Treagust, D. F. (2002). Teaching about the gene in the genetic information age. *Australian Science Teachers' Journal*, *48*(2), 20–24.

Wieman, C. (2017). *Improving how universities teach science: Lessons from the science education initiative.* Cambridge, MA: Harvard University Press.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*(4), 625–636.