SCIENTIFIC ANALOGY-ING: A COLLABORATIVE AND CRITICAL APPROACH TO (RE)GENERATING ANALOGICAL MODELS IN BIOLOGY

by

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

SCIENTIFIC ANALOGY-ING: A COLLABORATIVE AND CRITICAL APPROACH TO (RE)GENERATING ANALOGICAL MODELS IN BIOLOGY

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Bachelor or Science in Applied Learning and Development, 2017, The University of Texas

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Analogies pervade everyday life and are especially promising when thought of as models for teaching abstract scientific concepts. Problems arise, however, when teacher-generated analogies fail to draw from source domains that match students' experiences. Self-generated analogies have emerged as a possibility for students constructing scientific explanations but have been far less researched than the use of teacher-generated analogies. A related strategy being explored in recent years is the collaborative construction of scientific analogies. Student-generated analogies, like any model, should be critically examined and their applicability should be negotiated with students. This qualitative action research study describes the ways in which collaboration between peers and critical analysis of the strengths and limitations of analogical models may support the writing process for biology students (re)generating scientific analogies. The research question guiding the study was: In what ways, if any, does a collaborative and critical learning environment support student analogy (re)generation in science?

INTRODUCTION

> And what do teachers do when they see the worried looks on their students' faces in the middle of an abstract explanation? They reach for an analogy or a model and this may explain the frequent use of analogical models in science lessons. (Harrison & Treagust, 2000, p. 1014)

The mitochondrion is like the powerhouse of the cell. This analogy has been used for ages to draw a comparison between the assembly of ATP molecules in the mitochondria and the generation of electrical energy in a power plant. This is an example of an analogy, a statement that features a comparison of two entities (Aubusson et al., 2006). Analogies are aptly referred to by Harrison and Treagust (2006) as “two-edged swords” (p. 11) because of their potential to both foster and complicate scientific understanding. Recently, I spoke to a former teacher who serves as a rater for the AP Biology test. She lamented low scores on an essay prompt that asked for a description of each cell organelle and its role in the cell. She explained that an astounding number of students missed the question because they described the cell organelles as part of an analogy. She gave examples of students comparing the nucleus to the captain of a ship because it directed cell activity or the lysosome to a garbage dump, collecting and processing waste. Her conclusion to the end of her story was to encourage the nearby biology teachers, including myself, to stop using analogies in science! Though this is one conclusion that can be drawn, other perspectives may interpret this frustrating situation differently.

Analogies cannot be avoided because they are critical components of scientific thinking and play a significant role in the development of scientific knowledge (Niebert et al., 2012). Science as a field has a long history of employing analogical reasoning to grapple with abstraction. For example, early explanations of heat transfer were based on an analogy comparing the movement of heat from areas of high to low temperature to the flow of water in a waterfall from high to low areas. This has allowed for further predictions related to thermodynamics to stem from the analogy of “heat flow” (Haglund, 2013). Similarly, much of what is known of electrical circuits was developed within an analogical structure likening electricity moving through wires to water moving through pipes. The mapping of relationships from a known entity (water in pipes) to the unknown (electricity in wires) allowed scientists to generate new theories of how circuits behave (Farinella, 2018). Analogies, referred to in the scientific community as “analogical models”, are “the methods and products of science” (Harrison & Treagust, 2000, p. 1014). If I were to return to the conversation with the AP exam rater, I might point out that biology teachers, or any teacher for that matter, cannot simply stop using analogies in science teaching, rather teachers should consider *how* they use these tools as part of instruction.

MAIN BODY

Problem, Rationale, and Research Question

Analogies have long played a role in the development of scientific knowledge (Farinella, 2018; Haglund, 2013) and are especially promising when thought of as models for teaching abstract scientific concepts (Aubusson et al., 2006; Coll, 2006). Problems arise, however, when teacher-generated analogies fail to draw from sources of knowledge that match students' experiences (Niebert et al., 2012). Student-generated analogies have been offered as an alternative that would better bridge students' prior knowledge with target science concepts being learned (Haglund & Jeppsson, 2012; Lancor, 2013, 2014; Pittman, 1999; Wong, 1993). Though promising, analogy generation is difficult for students (Zook, 1991). Social learning theory (Vygotsky, 1962) would suggest that students may find it easier to generate analogies with the help of others. A major critique of analogies as learning tools in science classrooms is their potential to be misinterpreted or overextended, leading to misconceptions (Niebert et al., 2012); however, modeling perspectives suggest this may be resolved by negotiating the applicability of analogies and supporting students in evaluating the limitations of analogies (Aubusson et al., 2006; Coll, 2006; Schamp, 1990).

This study seeks to describe middle school biology students' experiences as they (re)generate[1] analogies to model abstract science concepts. The unit implemented for this study infuses the practices of collaboration and critique throughout the analogy (re)generation process to further investigate how these components can be leveraged to support students in generating analogies and using analogical reasoning to explain science concepts. I have attempted to shine

[1] I use the term (re)generation to refer to the process by which students generated analogies then revised or entirely rewrote their analogies as they critically evaluated the limitations of analogies. Students both generate and regenerate analogies, necessitating the use of the term (re)generation.

light on the following research question: *In what ways, if any, does a collaborative and critical learning environment support student analogy (re)generation in science?*

Literature Review

In my review of literature, I bring together cognitive and social theoretical perspectives as well as the established body of research on analogies in science education to position my study and inform my research question.

Theoretical Framework

This study is informed by constructivist theories and additional perspectives on experientialism. Constructivism is an interpretive framework through which knowledge is viewed as being actively constructed by individuals and meaning as formed through interactions with others (Creswell & Poth, 2018; Merriam & Tisdell, 2016). In the context of science education, constructivism is interpreted as a theory of learning in which students' prior knowledge largely affects the construction of new knowledge, and social and historical contexts play a role in knowledge construction as well (Niebert et al., 2012). Niebert et al. (2012) point out that constructivism is, in some ways, insufficient for theorizing analogy learning and presents experientialism as an additional layer needed to understand the role of analogies in science education. They summarize findings from linguistics, philosophy, science education, and neurobiology which "show that abstract concepts—this refers to most concepts in science—are not understood directly but in terms of other domains of knowledge; that is, understanding is ultimately grounded in embodied experience" (p. 852). This translates to science education as a need for students to ground what they learn in their own experiences. This becomes especially necessary as students advance academically through increasing more abstract science content.

Gentner's (1983) structure-mapping theory provides a model of how students bridge personal experiences and abstract science concepts. Gentner's framework (1983) describes the process of learning abstract science topics as an analogical process wherein students must map a familiar experience (the analog or source domain) onto an unfamiliar new concept to be learned (target domain). This occurs when the target domain has not or cannot be experienced directly. Science learning, then, can be supported by helping students directly compare abstract scientific concepts to familiar things they experience every day. For example, the *cell as a city* analogy is often used in life science classrooms. Cell organelles are entities that are too small to be observed directly therefore this topic requires a certain level of abstraction to understand. A city is something that most students are familiar with and can serve as a source domain. To help students better understand how each organelle functions within the cell, a series of analogies compares each organelle (the science target concept) to a part of a city (the source).

- *The Golgi apparatus (target) is like a post office (source) because it packages materials for transport.*
- *The cell membrane (target) is like a fence around the city (source) because it provides protection and allows materials in or out.*

In this way, the analogy serves as conceptual bridge from the known to the unknown.

Analogies and Science Education

From a linguistic perspective, analogies are devices that overtly point out similarities and differences between two entities (Aubusson et al., 2006; Niebert et al., 2012). An analogy may read as: *the mitochondrion is like the powerhouse of the cell because it is a site where energy is made usable*. A well-developed analogy may even include such a statement as *the mitochondrion is unlike a powerhouse because transforming mechanical energy into electrical energy using a* *generator is a completely different process from the metabolic chemical reactions that occur within mitochondria*. In the context of science education, analogies are recognized as language used by teachers or students to highlight similarities and differences between a source concept and a scientific target concept. Analogies in the science classroom may also be referred to as instructional analogies (Eskandar et al., 2013) or pedagogical analogical models (Davis, 2013; Harrison & Treagust, 2000).

Analogies used in science education may be found in textbooks and other curricular materials, developed by teachers as explanatory tools, or generated by students themselves. Analogies used or created by teachers do not necessarily help students learn (Eskandar et al., 2013; Niebert et al., 2012) because they rarely draw from source domains that match the embodied experiences of students. Research suggests that students may not comprehend the connections being made unless the student is familiar with the source domain and can successfully map characteristics from the source to the target science concept (Niebert et al., 2012; Zook, 1991). For example, a teacher may compare gene expression to the selectivity of reading a phonebook. *A cell does not transcribe the entire genome like a person does not read a phonebook in its entirety. Rather, only certain genes are "read" like the select few pages a person reads when seeking information in a phone book.* The problem arises here because many students in today's classrooms have never seen or used a phonebook and may become more confused by this analogy. The source (reading selected parts of a phonebook) would not be successfully mapped to the target science concept ("reading" selected genes within the genome) because the student is unfamiliar with the source (Zook, 1991).

Student-generated analogies offer an alternative that would allow students to select sources from their everyday lives and interests. By writing their own analogies, students connect entities they have directly experienced to the target science concept, allowing them to more successfully construct new scientific knowledge (Gentner, 1983; Niebert et al., 2012). Research suggests that student-generated analogies have the potential to better facilitate connections between students' prior knowledge and scientific concepts to be learned (Haglund, 2013; Haglund & Jeppsson, 2012; Lancor, 2014; Pittman, 1999; Wong, 1993). Despite their promise, student-generated analogies present a challenge: while teachers may easily generate analogies, these are more difficult for students to map and use and, conversely, student-generated analogies are more useful to students but are difficult for students to create due to their lack of familiarity with the science topics at hand (Harrison & Treagust, 2006; Treagust et al., 1998; Zook, 1991).

Analogies in Practice

Analogies and models are often conflated in the science education literature largely due to their common origins. Scientific models are analogical structures and analogies function in science as models. Harrison and Treagust's (2000) typology of analogical models used in science classrooms, acknowledges verbal analogies as one of many types of models. Lehrer and Schauble (2000, 2012) acknowledge that models are based on the same structure-mapping (Gentner, 1983) framework that characterizes analogical reasoning. Despite their shared underlying structure, concrete models that are physical and visual in nature are more readily used in science classes than verbal analogies (Harrison & Treagust, 2000). This may be due to the increased focus on modeling in recent curriculum initiatives, lack of attention to the potential of analogies, or concerns about the ambiguity of science analogies.

Historically, the use of models in science classrooms has primarily been as a pedagogical tool for teachers to illustrate phenomena (Lehrer & Schauble, 2012). More recent perspectives on modeling argue instead for models to be approached in ways consistent with the discipline of science. Recent curricular emphasis such as *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (National Research Council, 2012) and the *Next Generation Science Standards* (NGSS) (NGSS Lead State, 2013) frame modeling as a disciplinary practice and suggest that students construct, revise, and evaluate the limitations of models as a scientist would. Educational research has also taken up this approach to modeling as a practice that generates new knowledge (Harrison & Treagust, 2000; Lehrer & Schauble, 2000, 2012). Schwarz et al. (2009) identified four essential elements of modeling practices; student construction of models, student use of models, student evaluation of models, and student revision of models.

While the literature recognizes that scientific models are analogous structures (Gentner & Toupin, 1986; Lehrer & Schauble, 2012) and analogies can be classified as models (Treagust et al., 1998), the link between models and analogies has failed to translate to curriculum or classrooms. Analogies are not addressed in any widely recognized national curriculum documents or recognized as examples of models. Curriculum (National Research Council, 2012; NGSS Lead State, 2013) and teaching practices reflect the importance of students creating and evaluating models, but this importance is rarely extended to analogies. In the literature on science analogies, analogy writing has been recognized as a generative practice rather than an illustrative product (Wong, 1993) which has spurred more research on student-generated analogies; however, only a few of these studies include evaluating analogies (Lancor, 2013, 2014) or revising analogies (Haglund & Jeppsson, 2012).

One reason for the avoidance of analogies as science learning tools may be existing concerns about analogies in science. The use of analogy in science education has been critiqued due to its tendency to highlight similarities between two entities but hide key differences (Lakoff

& Johnson, 1980; Niebert et al., 2012). It has been argued that analogies can cause misconceptions if students do not recognize their limitations (Harrison & Treagust, 2006). Analogies may be underutilized due to teachers' concerns that students will develop misconceptions that lead them away from accepted knowledge of science (Haglund, 2013). This critique is also true of scientific models, which intentionally select and amplify certain characteristics over others (Lehrer & Schauble, 2012). Perspectives on scientific modeling, however, accept the sacrifice of perfect truthfulness in exchange for conceptual clarity (Maksic, 1990) and emphasize the importance of teaching students to consider limitations of models (Schamp, 1990) and the nature of models (Coll, 2006).

> Analogical models are always 'simplified' and 'exaggerated' in some way to emphasize the attributes that are shared between the analogical model and the target concept. Despite careful planning to reduce the unshared attributes, analogical models always break down somewhere. (Harrison & Treagust, 2000, p. 1019)

If analogies are more consistently framed as models, misconceptions may be mitigated by taking a more critical approach in which the applicability of specific analogies is negotiated with students (Aubusson et al., 2006) and efforts are made to examine their limitations.

Social Perspectives

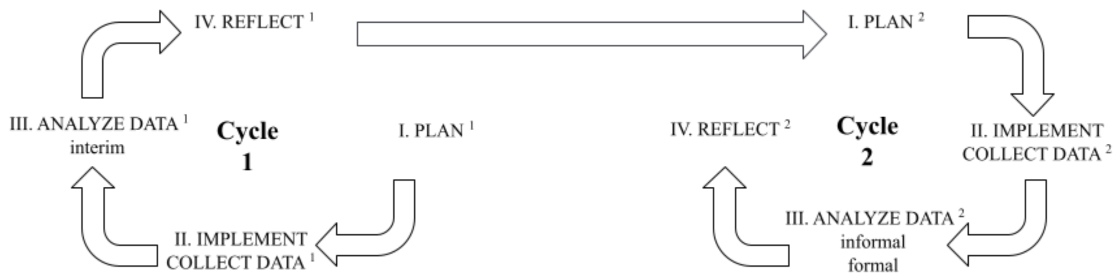
Though early analogy research in science education has its roots in cognitive science (Gentner, 1983), there has been a push toward social theory (Haglund, 2013). Focus has shifted from the individual to collaborative approaches in which students may work in groups to generate analogies (Bellocchi & Richie, 2011; Haglund & Jeppsson, 2012) or serve as sources of feedback (Pittman, 1999) during the process. A social emphasis within analogical reasoning is consistent with its constructivist character. Utilizing the social environments of students can better position them to receive support from others, operate within their Zone of Proximal Development, and co-construct more meaningful knowledge (Vygotsky, 1962). Analogy generation can be difficult for students (Harrison & Treagust, 2006; Treagust et al., 1998; Zook, 1991) which is reasonable considering the cognitive demand of establishing connections within a domain of knowledge not yet fully understood. Collaborative learning stands to help resolve some of the challenges faced by students and support analogy generation. "From the point of view of research on analogies, the social setting provides an opportunity to come up with more potential source domains and scrutinize them from more perspectives than individual students would be able to do by themselves" (Haglund, 2013, p. 59). Research exists on the collaborative construction of scientific analogies between peers (Haglund, 2013) and between students and teachers (Clement, 2013). Though rare, socially generated student analogies do occur and can be capitalized on by teachers to support science learning (Harrison & de Jong, 2004). Though research exists on collaborative generation of analogies among students, no studies (to my knowledge) combine this approach with a generative stance on analogy writing.

Method

Action research is implemented in one or more cycles (Hendricks, 2017; Herr & Anderson, 2005; Merriam & Tisdell, 2016). A typical cycle includes identifying a problem, planning an actionable component, collecting and analyzing data, and reflecting on findings to inform further action. This study consisted of two cycles: Cycle 1 and Cycle 2. In Cycle 1, I (I) planned classroom instruction, (II) implemented classroom instruction and collected data during the process, (III) systematically analyzed data, and (IV) reflected on findings and made changes to classroom instruction. In Cycle 2, I revised classroom instruction based on findings from Cycle 1 and repeated phases I-IV. The action research cycle structure is illustrated in Figure 1.

Figure 1

Action Research Cycle



Because research took place in the evolving local context of a school campus and the unpredictable global context of pandemic, the original research and teaching design elements had to be negotiated during the time period of the study. Alterations had to be made to the instructional calendar due to curricular needs and some of the instructional tools used had to be adjusted due to broader district-level requirements. Additionally, data analysis differed between Cycle 1 and Cycle 2 and will be discussed in detail in the data analysis section. The principles of action research design allowed for such fluctuations (Hendricks, 2017). Human subject research was approved (TCU IRB 1920-299).

Participants, Setting, and Study Context

Stemmons Middle School[2] serves nearly 600 sixth, seventh, and eighth-grade students. Bloomfield ISD is a public school district located in a suburb of a large metropolitan area in North Texas. Stemmons Middle School is a relatively new campus in its seventh year. The school had a humble beginning in an unused wing of the district high school but soon moved to a revitalized elementary school building re-designed to emulate the modern and innovative culture

[2] All names people, places, and schools are pseudonyms

Stemmons embodies. Windowed classrooms and exposed wiring encourage teachers and students to constantly observe and question the space around them. Stemmons has a clear campus culture defined by collaboration, empowerment, restorative practices, and celebrations of growth. Elements of project-based and inquiry-driven learning are evident in most classrooms and students are provided with tools and systems that encourage goal setting and ownership of individualized learning. Students and teachers are assigned to "houses" that build community and a sense of belonging.

Stemmons Middle School is also unique in its role as a campus of choice within a district that prioritizes choice in students' academic experience. Bloomfield ISD strives to empower students in choosing personally relevant educational paths and, as a result, offers five schools of choice at the elementary level, two at the middle school level, and two at the high school level. Schools of choice are available to all students zoned for the district, regardless of academic performance, ability, English proficiency, or socio-economic background. The student body at Stemmons is selected through a blind lottery. Students who wish to attend Stemmons enter their names into the lottery. Each school of choice comes with its own curricular emphasis and campus culture continually upheld by the student population that has elected to enroll there. As a school of choice, Stemmons' campus identity is centered on inquiry and emphasizes innovations, particularly in the areas of Science, Technology, Engineering, Art, and Mathematics (STEAM). Academics and fine arts are the biggest influence as there are no athletics. Students enrolled at Stemmons can participate in sports at the traditional zoned campuses. Studio art classes, band, choir, and drama are major campus activities. Extracurricular activities include language clubs, LEGO® robotics, Drone Club, gaming clubs, and several service organizations. It is important to note that a student's choice to attend Stemmons makes a statement about their academic identities. Most students identify with the campus culture of inquiry and innovation which sets this campus apart from what might be encountered in more traditional contexts.

Stemmons' student population consists of 72.4% white, 18.5% Hispanic, 4.5% African American, 1.4% Asian, .3% American Indian and 2.7% students of two or more races. Within the student body, 21.4% of the students are recognized as economically disadvantaged, 30.0% of the students are considered at-risk, and 4.1% of the students are emerging multilingual[3]. Demographically, the participants in this study are relatively representative of the student population. The participant group consisted of three boys and three girls.

Participants in my study are eighth-grade students enrolled in my Pre-AP biology class. Class periods are 50 minutes each day and the class size was 11 students at the start of this study. Pre-AP biology is a high school credit course traditionally undertaken by ninth and tenth-grade students. The students enrolled in my class are members of an accelerated mathematics and science program. As sixth graders, they took accelerated science covering all middle school science standards. As seventh graders, they took Integrated Physics and Chemistry, another course offered at the middle school for high school credit.

I taught science at Stemmons Middle School for four years. My experience in education began in a literacy-specialized teacher preparation program where I developed a foundation in reading, writing, and language instruction that I have since transferred to a departmentalized science context. I hold an early childhood through sixth-grade generalist certification as well as a seventh through twelfth-grade science certification. My experience as a researcher has developed alongside my experience as a practitioner. My first experience in collaborative action research

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[3] Demographic data is from the 2019-2020 Texas Academic Performance Report

took place during my student teaching placement. My cooperating teacher, my field supervisor (both doctoral students) and I conducted a study to explore action research to understand the complexities of teaching by investigating questions of educational equity, access in curriculum designs, and our pedagogies (Daly-Lesch et al., 2018). Engaging in action research as a pre-service teacher disrupted my previous notion that academic research was conducted only by seasoned academics. I was granted access to something I thought of as defined by a currency of experience. I now consider action research to be a component of my developing teaching identity. By participating in action research early in my teaching career, I adopted reflective practices which became ingrained in my teaching and continue to define my practice today.

This instructional year has been characterized by unforeseen challenges due to COVID-19, and learning has adapted. The school district allowed students to choose the location from which they will attend class: physically present in the classroom or virtually present from their homes. Students elected to learn virtually were synchronously present during using a teleconferencing program. During the study, three students learned entirely virtually and three students learned entirely in-person. To support virtual students, the school district implemented a blended learning model. The district adopted an online learning management system and a curriculum with synchronous and asynchronous components. The activities associated with this unit of study were mostly synchronous with both in-person and virtual students interacting and learning during class time. Student work products were created and submitted within the district online learning management system and students interacted on discussion boards within the district learning management system. The district mandated universal curriculum across classrooms and campus with a strict day-by-day scope and sequence but teacher-planned learning activities are permitted on designated days. The lessons described in this study were implemented on days designated as teacher planned. Both in-person and virtual learners receive the same curriculum and learning activities.

At Stemmons, collaboration and critique have historically been championed as an essential part of the learning process, but challenges related to COVID-19 have reduced the incidence of these factors in student learning. During sixth and seventh grade, these students had extensive opportunities to collaborate, often with other members of the cohort. The learning framework present in all classrooms prior to COVID-19 required that students work in groups and have opportunities to give and receive constructive critiques of their learning products. As a result, these students may be more practiced in collaboration and critique than the average middle school student. During the year in which this study took place collaboration and peer critique were negatively impacted by the increase in students learning virtually and the difficulty of communicating under social-distancing protocols.

Another challenge presented by the current educational climate was differential access related to each family's choice to attend school in person or virtually. I was tasked with providing an equitable experience for students who physically attend my classes and students who attend virtually through a video platform. Given the historical and modern emphasis on manipulative aspects of science education, issues of equity and access arose for groups of students who are not physically present in the classroom. Under social-distancing guidelines and with a portion of students learning virtually, communication between classmates needed to evolve substantially to ensure all students have access to valuable social learning.

These new realities, while daunting, were an ideal environment for action research. Action research from an inquiry stance (Cochran-Smith & Lytle, 2009a; 2009b) has the potential to transform teachers' professional identities and act as a tool by which practitioner researchers may wrestle with institutional pressures and questions of equity and access (Schutz & Hoffman, 2017). As a researcher, practitioner, and participant, I had the opportunity to study my practice while also inquiring about my students' learning experiences. My professional identity will continue to evolve as I navigate curricular demands, question the institution of school science, and continue to think about ways to ensure that science is equitable, accessible, and meaningful for every student in my classroom.

Action Plan

The action component of an action research study situated in a classroom typically consists of some instructional component implemented by the practitioner-researcher with the immediate goal of addressing the research questions and the subsequent goal of improving one's own pedagogical practice (Hendricks, 2017). As a teacher, I have often used analogies to convey complex scientific processes, but these have been teacher-generated, and as such, they are not always useful to students. For this action research study, I adapted and implemented instructional strategies in which students generated their own analogies to explain biology concepts. The sequence and content of classroom activities will be described in detail in the implementation section to follow. As the teacher, I engaged the students in discussions about analogies as models and the limitations of physical and analogical models. During this process, students were encouraged to collaborate through online discussion boards and critique their own analogies as well as the analogies of their peers. As a researcher, I made observations and took field notes (Appendix A), attempting to gain insight from my students and adjust my teaching accordingly. I also engaged students in virtual focus group discussions (Appendix B) where I gathered my students' thoughts about science analogies, perceived effects on their learning, and perceived challenges. They provided useful feedback about the learning activities which informed the planning of the next cycle.

Instructional Planning

The topic chosen for Cycle 1 was *energy in living systems*. This topic was selected because understanding energy requires abstraction as energy is not something we can directly observe. The topic selected for Cycle 2 was *matter and energy in metabolic processes*. This topic was chosen to complement and extend upon the topic explored in Cycle 1. This is also a highly abstract topic due to the atomic scale of metabolic processes. Highly abstract concepts such as energy and matter are ideal for analogical reasoning due to the inherent need for mapping source domains onto topic domains we cannot experience directly (Niebert et al., 2012).

Students need proper scaffolding to supply effective critique (Chang & Chang, 2012). As criteria for critiquing analogies, I introduced students to a *highlighting and hiding* conceptual framework adapted from Lakoff and Johnson (1980) where *highlighting* refers to the science concepts explained by the analogy and *hiding* refers to the limitations of the analogy or the concepts that are not explained. Students practiced applying this framework in whole-class activities before utilizing it during self and peer critique.

The Focus, Action, Reflection (FAR) guide for teaching with analogies was developed (Harrison & Treagust, 2000; Treagust et al., 1998) to help teachers facilitate students through a reflective approach to interpreting analogical models. I found value in the FAR guide, but this is designed for pre-existing curricular analogies (Davis, 2013; Sickel & Friedrichsen, 2012) not student-generated analogies. I adapted some elements of this model for my instructional component such as explicit mapping of the source domain to the target concept. Treagust et al. (1998) emphasize the importance of supporting students in mapping analogical relationships.

> The systematic mapping of true inductive analogies promotes deep understanding but is difficult for unskilled learners to transact. While surface similarities cue the learner to the analogical possibilities, it is the systematic mapping of relations between the analog and the target that transfers process knowledge from the analog to the target. (p. 87)

I provided further scaffolding by using a Student Analogy Guide (Appendix C) template adapted with permission from Rachael Lancor (2014) to facilitate students through mapping the components of their analogies and identifying highlighted and hidden concepts.

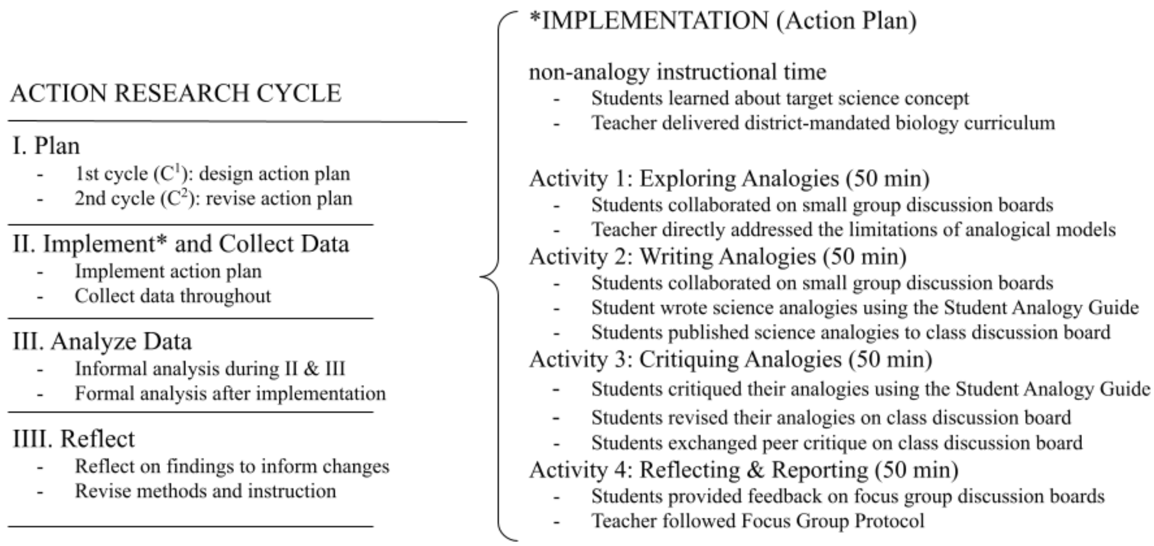
Implementation

During the implementation phase of the action research cycle, I facilitated the instructional plan for the study which is described below. In the first activity of Cycle 1, I led class discussions around scientific models and their limitations. I introduced the *highlighting and hiding* framework and students applied the framework to critique existing models from curricular materials. In the second activity, students were tasked with writing (generating) an analogy that compared the science target concept *energy in living systems* to a familiar source concept of their choice. Students collaborated on discussion boards during the writing process and published their finished analogies to a class discussion board so that all students could see analogies written by their classmates. During the third activity, students utilized their Student Analogy Guides to map the comparisons and characteristics of their analogy and critique their work using the *highlighting and hiding* framework. On the discussion boards, students exchanged peer critique using the same framework. Students were encouraged to (re)generate their analogy if they gained the insight to do so from the critique process. Students chose to (re)generate their analogy by extending the analogy, replacing the analogy with a more appropriate one, or generating a second analogy to complement the first. The fourth activity required students to respond to reflective prompts in focus group discussion boards.

After much reflection around my observations and students' work products, I chose *matter and energy in metabolic processes* as the topic for Cycle 2. I selected this topic because students' analogies from Cycle 1 reflected their understanding of energy as quantifiable, transferable, and measurable but revealed some naive conceptions about energy conservation. I decided that tracing matter and energy in metabolic processes would tease out and address their misconceptions. Our first activity integrated and extended ideas from Cycle 1 through discussions of phenomena such as plant growth, decomposition, and fat loss. Students then explored a teacher-created model of photosynthesis and cellular respiration and critiqued its strengths and limitations. Finally, students returned to their analogies of *energy in living systems,* evaluated the extent to which energy appeared to be conserved in their analogy, and revised their analogies once more. The second, third, and final activities in Cycle 2 mirrored closely their counterparts from Cycle 1. Students once again generated, critiqued, and (re)generated analogies this time modeling *matter and energy in metabolic processes*. An abbreviated visual of the instructional implementation (action plan) can be found in Figure 2.

Figure 2

Instructional Implementation Embedded Within the Action Research Cycle



Note: The action research cycle was conducted twice: Cycle 1 (C^1) and Cycle 2 (C^2).

It should be noted that the instructional component was intended to position students to engage with science analogies in ways that are consistent with elements of modeling practices. Schwarz et al. (2009) identified four elements of modeling practice in science: constructing, using, evaluating, and revising models. Creating models is a key disciplinary practice in science and an essential component of modeling as a practice. By generating their own analogies, students effectively created analogical models. All students used analogies in their interactions with peers. In sharing their products on class discussion boards, students used their analogies to explain science concepts to others. The self and peer critique processes served as an evaluation of the extent to which each analogy could be used to explain a science concept. Finally, informed by critique, students revised their analogies.

Research Question

The research question guiding the study was: In what ways, if any, does a collaborative and critical learning environment support student analogy (re)generation in science?

It is important to note that the purpose of this study is not to objectively evaluate or compare the quality of analogies produced by students as these analogies are representative of students' interpretations and it is not my place as a teacher or researcher to say whose analogy is more scientific. Rather, I hope to shine light on the question of IF and HOW collaboration and critique may support students in the analogy (re)generation process.

IF students are supported in the analogy (re)generation process, I anticipate that they will succeed at the task by producing functional analogies. In Lancor's (2013, 2014) study of student-generated analogies, thirteen of her participants failed at the task of analogy writing. Rather than comparing a science topic to something else, they described or drew the science topic. In the context of this study, a functional analogy is one that accurately and logically compares at least one characteristic of a science topic to another entity. In exploring HOW students are supported during the analogy (re)generation process, I will rely on my own interpretations of the data and students' self-reported perceptions of support and perceived quality of their analogies.

Sample Selection

Creswell and Poth (2018) write about five common approaches to research. In describing my sample, I used the language of the approach that best fits my study design: a case study. This study utilized purposeful sampling in which the sample is not intended to be a subset of the population from which to generalize findings, rather the sample is chosen for their potential to shine light on the topic of the study (Creswell & Poth, 2018). Students in my own classroom were able to provide me with a better understanding of the role of collaboration and critique in generating science analogies so that I can improve the implementation of such learning activities. Additionally, I purposefully selected my biology class rather than my sixth-grade science classes because of the frequency of highly abstract concepts in biology. Highly abstract concepts cannot be directly experienced (Niebert, 2012), which necessitates structure mapping between source and target domains (Gentner, 1983). For this reason, biology students were an ideal population for this study due to their frequent encounters with scientific concepts requiring abstraction.

Two-tier sampling is a common strategy within case studies (Merriam & Tisdell, 2016). In two-tier sampling, the case is purposefully selected, and a second tier of sampling occurs within the case. I considered the first tier a bounded case composed of myself and my eleven eighth-grade students enrolled in Pre-AP biology course. The second tier of sampling occurs when selecting whom to analyze within the case. This second-tier sampling was dependent on ethical consideration as well as sampling strategy.

Due to considerations of power dynamics associated with my position as the teacher of record, the study was conducted as a blind study. All students participated in classroom activities related to the study because this was their regularly scheduled classroom experience. I collected data for all students because a maximum variation sample allowed me to better understand the range of student experiences. All student data were subject to interim analysis at the end of Cycle 1 and moving into Cycle 2. After all grades had been finalized for the academic year, I determined which students had assented to the use of their data. Sources of data from assenting students were retained and further analyzed while any sources of data from students who had not given assent were deleted. Of the original eleven students enrolled in the biology class and therefore part of the Tier 1 sample, six students were included in the Tier 2 sample. Two students did not assent to participate. Three students assented but were excluded from analysis. The first student was excluded because his group members were non-participants which prevented analysis of group discussions. The second student was excluded because she was absent more than half of the instructional implementation days during the study. The third student was excluded because he transferred to a different school at the start of the study.

I examined the six selected participants as three pairs of students. I considered these to be embedded cases within the larger case of the biology class and subject to cross-case analysis. Each student pair included one student learning in-person and one student learning virtually from home. Student pairs collaborated by posting synchronously and, at times, asynchronously to online discussion boards. Most communication was in real time during class but occasionally students posted to discussion boards outside of class. All names used are pseudonyms chosen by the participants.

One aspect of Action Research that differs from many other approaches is the consideration of the researcher as a participant in the study. I selected such a methodology because it would allow me to study my own practice within my classroom. My unique positionality within the study is described in the following section.

Researcher Positionality

Recognizing the effect of my positionality in my own research is critical for considering the biases that may affect my project. Herr and Anderson’s (2005) continuum of positionality outlines a spectrum of researcher locales from that of an insider, who studies a context from within, to that of an outsider, who conducts research on a context. As a practitioner participating in a study of my own classroom, I am situated as an insider relative to my research.

The insider role offers both affordances and challenges. As an insider, I have an in-depth understanding of the context and have previously established relationships within my district, campus, and classroom that would be difficult to attain as an outsider, but my insider status can also interfere with my ability to remain objective. By identifying myself as an insider, I seek to avoid a pitfall identified by Herr and Anderson as the “outsider-within” (2005, p. 46). These researchers warn that “to downplay or fail to acknowledge one's insider status is deceptive and allows the researcher to avoid the kind of intense self-reflection that is the hallmark of good practitioner research” (p. 47).

My positionality as the teacher of record in the classroom under study makes it inevitable for my influence to affect the data and complicates my interpretation. For example, students may have felt pressured to tell me what they assume I want to hear given my position of power as the adult and classroom teacher. To combat this inclination, I emphasized the value of constructive feedback and transparency in research in class. During analysis, I cross-referenced data sources to ensure that the emergent themes I recognized were being directly acknowledged by the students themselves. I also informed students of the blinded structure of the study and remained blind until all grades had been finalized for the academic year. Still, I acknowledge that these measures cannot remove my influence in the classroom. I do not intend to claim that any of my findings are absolute. I report only my perceptions and my attempts to view the data from multiple interpretive standpoints.

One strategy for navigating my personal biases is to seek the perspectives of an outsider critical friend to help uncover my assumptions and confirm my interpretations. A critical friend is defined by Costa and Kallick (1993) as “a trusted person who asks provocative questions, provides data to be examined through another lens, and offers critique of a person’s work” (p.

50). Following Hendricks (2017), I sought the help of a critical friend to think through how my familiarity with the study context may be manifesting in my assumptions. I conducted a peer debrief with this colleague, sharing representative sections of my data analysis. This session allowed me to present my interpretations to an outsider and help me better ground my findings. My peer confirmed that she would have come to the same findings given the data set.

Another concern related to my aforementioned insider status is the tendency of insiders to attempt to study the outcome of some intervention and underplay personal ties to the project, deceptively promoting oneself (Herr & Anderson, 2005). I am in no way promoting the use of my specific lesson structures to an outside audience, rather I am attempting to better understand how collaboration and critique might be leveraged within the context of student analogy (re)generation.

Finally, I must consider aspects of my personal experience that may influence my perceptions. My background in both literacy and science education and inclinations toward content integration contribute to a significant personal bias toward strategies that bridge science and literacy learning. I had a positive experience throughout my education, especially in reading, writing, and science classes which may affect my assumptions about the experiences of my students. Students themselves may not value border-crossing between content areas or the use of figurative language in science spaces and it is important that I manage my assumptions and preserve any and all student perspectives. I kept this in mind during analytical procedures, but I also acknowledge that research is not void of human influence. Qualitative research such as mine relies on the researcher as the analytical tool and, by nature, does not claim to be objective.

Data Collection

Case studies necessitate several different forms of data (Creswell & Poth, 2018; Yin, 2014). I collected transcripts of students' posts and comments to online discussion boards as well as Student Analogy Guide work products (Appendix C) from each student. I also acted as a participant-observer, making observations during class and recording them as field notes (Appendix A). Finally, I conducted focus group sessions (Appendix B) on another discussion board and collected transcripts. These sources of data will be referred to as *transcripts*, *work products*, and *field notes*.

Transcripts included records of small group discussion boards, whole class discussion boards, and online focus group discussion boards. Discussion boards were a feature within the district-mandated learning management system and transcripts of these discussion boards were exported from the system and transcribed into one text document for each student group.

Work products or Student Analogy Guides were digital templates in the form of Google Documents assigned through the district-mandated learning management system. These were completed and submitted by students before being exported from the system for analysis.

Field notes were both descriptive and reflective in nature. As a participant observer, I made observations and took field notes during class time and expanded my notes into reflections outside of class. Field notes pertaining to participants were retained, organized according to student groups, and transcribed into one document for analysis.

Data Analysis

Interim Data Analysis

A common characteristic of qualitative research and of action research is that data analysis takes place throughout data collection (Creswell & Poth, 2018; Merriam & Tisdell, 2016; Miles et al., 2014). Interim data analysis is a preliminary form of analysis often employed between or within cycles of qualitative action research. During Research Cycle 1, I conducted interim data analysis to inform Cycle 2. During Interim Analysis, I conducted analysis at the level that any classroom teacher would analyze the work of students. I examined student learning products and noted strengths and weaknesses. I noted successes, challenges, and suggestions brought up during focus groups that inform changes I made to my instructional strategies. I reviewed my field notes for any information that helped me improve my teaching as I prepared to implement Cycle 2. In the interest of protecting student confidentiality, all research data analysis were delayed until grades had been finalized for the academic year. No student data were exported from the district learning management system until this point; however, all student data were subject to interim analysis regardless of participation as it is expected for any teacher to examine student work and use new insights to make instructional decisions.

Informal Data Analysis

Miles et al. (2014) emphasize the importance of processing raw data before analysis. I did this after all grades had been finalized for the academic year. Posts and comments from participants on discussion boards were transcribed into a single word document for each student group and saved as a digital file. These transcripts included small group, whole class, and focus group discussion boards. Student Analogy Guides belonging to participants were exported from the district learning management system and saved as digital files. Field notes were transcribed into a single word document. Notes associated with non-participating students were deleted. During processing, I engaged in two forms of informal analysis: jots and analytical memos (Miles et al., 2014). As I copied, transcribed, and organized the data set I utilized comment features to add digital annotation to specific pieces of data. Jotting captured my fleeting thoughts and observations as I noticed instances in the data set that related to the research questions. As I recorded these brief jots, I noted connections between jots as analytical memos in a separate document, organized by date. Memos allowed me to preserve my thoughts about emergent patterns and links as well as problems and dilemmas I encountered.

Formal Data Analysis

I primarily utilized coding strategies associated with grounded theory research (Flick, 2018; Strauss & Corbin, 1994). This is an iterative process starting with open coding and moving into axial coding where emergent codes are condensed into themes (Merriam & Tisdell, 2016). Initially, the process was inductive and became more deductive as more data were analyzed and compared. Though there is not a prescribed analytical method for action research or case study, this “ground up” (Yin, 2014, p. 138) approach to data analysis is common. Often studies that are not grounded theory use the grounded theory sequence of open and axial coding because it is a structured and widely respected approach (Merriam & Tisdell, 2016).

In order to answer my research question (In what ways, if any, does a collaborative and critical learning environment support student analogy (re)generation in science?) I analyzed the discussion board transcripts, which include small-group and whole-class student dialogue in the form of posts and comments, as well as responses to online focus group prompts. Initial codes COLLABORATION and CRITIQUE were applied to all relevant sections of dialogue. It was common for data to be dual-coded as collaboration and critique as these practices overlap often in the classroom. Dialogue from the discussion boards that could not be coded as COLLABORATION or CRITIQUE fell into one of two categories: (1) student rapport (conversational, often comedic exchanges that do not serve an academic purpose) which was discarded or (2) students' analogy (re)generation which were analyzed chronologically in a separate stage of the analysis process.

Within the COLLABORATION and CRITIQUE codes, I used constant comparison to openly code for evidence of ways in which collaboration and critique may have supported student analogy generation. Several iterative rounds of open coding resulted in a list of descriptive codes. During the following process of axial coding, I condensed emergent codes into categories and re-coded the transcripts using the condensed scheme to ensure all data fit the scheme. I revised the scheme when necessary. Finally, I cross-referenced codes that emerged from both discussion group transcripts and focus groups. This was to ensure that I reported themes that were also acknowledged by the students themselves.

To supplement and further strengthen findings from open and axial coding of transcripts, I also incorporated elements of time-series analysis, specifically chronological sequencing (Yin, 2014). Using time stamps on student posts and the version history on their student work products, I chronologically sequenced students' (re)generations of their science analogies and discussion board dialogue. By synthesizing data sources in this way, I was able to examine ways in which students (re)generate their analogies over time and how collaboration and critique coincide with those changes. After sequencing textual data from work products, discussion boards, and focus groups, I wrote short narratives for each focal student and combined these to produce case summaries for each pair of students. Field notes were cross-referenced to further confirm and elaborate case summaries.

Trustworthiness

In *Improving Schools Through Action Research*, Hendricks (2017) synthesizes multiple sources widely referenced in qualitative studies to establish criteria for trustworthiness including credibility, transferability, dependability, and confirmability. To establish credibility, Hendricks (2017) suggests prolonged participation in the study context which is an embedded component of action research and is inherent in my design given my role as the teacher of the classroom being studied. Although transferability is not always a goal of qualitative research, I provided a detailed context description so that my research may be transferred to similar contexts if possible. I also retained an intact audit trail so that my methods can be traced by others and considered dependable.

While Hendricks emphasizes triangulation and neutrality as indicators of confirmability, I push back on this notion and instead offer crystallization (Ellingson, 2009) as an alternative. Neutrality is not achievable due to my insider positionality but, as noted by Ellingson (2009), accepting partiality is a central characteristic of crystallized research. Consistent with crystallization, I collected multiple forms of data (student discussions, student work products, observations, and focus groups). I engaged with my data through multiple interpretive lenses, examining the student experience from thematic and chronological standpoints. I presented data both as grounded themes and narrative descriptions, further emphasizing the multifaceted crystal-like nature of my data set. My positionality has been thoroughly discussed and, in the limitations section, I problematize the claims I have made. In doing so, my crystallized work gains reflective validity (Ellingson, 2009).

Findings

First, I describe grounded themes that commonly appeared across multiple cases. Then, I present case profiles to highlight differences between and within cases.

Grounded Themes

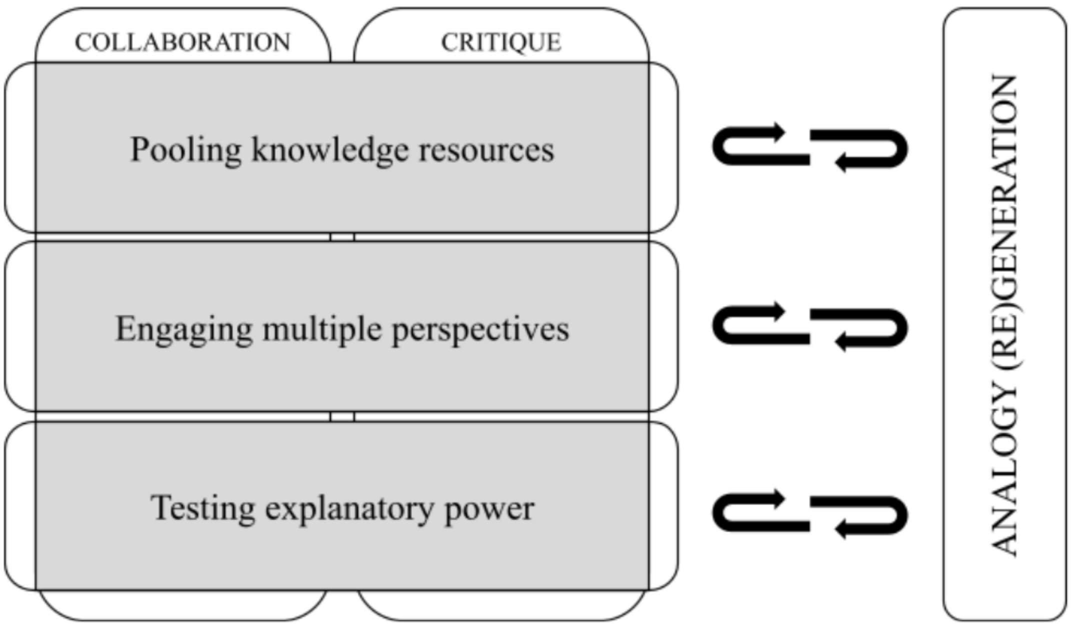
My findings suggest that elements of collaboration and critique were recognized as supporting students during the analogy (re)generation process. All focal students expressed some degree of positivity toward aspects of collaboration and critique. Some students expressed difficulty generating analogies, which was expected (Harrison & Treagust, 2006; Treagust et al., 1998; Zook, 1991), but several students reported that elements of collaboration and critique made the process feel easier.

A grounded approach to analysis yielded the following working model of how collaboration and critique support student analogy (re)generation. Across the focal cases, collaboration and critique appeared to support analogy (re)generation by allowing students to pool knowledge resources, engage multiple perspectives, and test the explanatory power of their analogical models. These factors operated continuously, not only supporting students' initial generations of analogical models but also their subsequent (re)generations. After generating an initial analogy, students cycled back into collaborative and critical spaces and returned to their work to (re)generate a more functional analogy that can better explain the target science concept.

Like all models, this model has limitations. This model does not account for significant overlap between collaboration and critique. Though some student actions may be exclusively collaborative or critical, some actions are both collaborative and critical in nature. The purpose of this model is not to separate and compare the role of collaboration and critique in supporting analogy (re)generation but to illustrate that both are equally valuable and highly compatible. Figure 3 illustrates three ways that this took place in my classroom.

Figure 3

The Role of Collaboration and Critique in Student Analogy (Re)generation



Pooling knowledge resources

Students had access to their peers and were encouraged to collaborate throughout the analogy writing process. All three groups chose to share their initial ideas with their group earlier in the process than I predicted, inviting feedback as their ideas formed. Across cases, students pooled their knowledge resources in ways that supported analogy (re)generation. Grant and Anjeli began by pooling their knowledge resources to co-create an initial idea for their analogies.

Grant: *What do you think we should do?*

Anjeli: *Maybe something about succession and energy levels*

Grant : *Ok. That sounds good, lets*[4] *do it. With energy levels, how could we compare that with something? same thing with succession.*

Anjeli: *I was thinking I could compare energy levels with like day to day life kind of how we lose energy while we go through our day just like the trophic levels*

Grant asks probing questions to help Anjeli focus her thoughts and Anjeli draws from the common experience of "how we lose energy while we go through our day." Though both students develop different analogies, similarities in their final products indicate that their products originate from this brainstorming conversation. Many students, including Grant and Anjeli, reported that the biggest challenge in analogy writing is getting started. This is consistent with Zook's (1991) model of analogy learning which states that student have the most difficulty selecting appropriate sources to draw from. In this example, collaborative pooling of knowledge supports both students in overcoming the hurdle of generating a new idea and selecting an appropriate source.

Students looked to each other as sources of additional knowledge not only in initial brainstorming sessions but also in small consultations during the (re)generation process. As Thea crafts and revises an analogy comparing cellular respiration to weaving and unweaving on a

[4] Minor grammatical errors may appear in student writing. For the sake of preserving the authenticity of student interactions, I did not correct such grammatical errors.

loom, she receives support from her partner, Ezra. Ezra provides an insightful observation that Thea's analogy could be expanded to describe both key metabolic processes.

Ezra: *I think that adding an area on photosynthesis would make it more complete, and give you a better understanding of cellular respiration as well.*

Thea: *Do you have any ideas on how to add photosynthesis?*

Ezra: *I think that a way you can word it is like buying the thread you collect all of the thread until you use it up eventually creating something and using up the thread. If you buy more thread you make something bigger and better.*

Thea responds to a critique from Ezra by further eliciting ideas from him, thus inviting him to pool knowledge resources. Her invitation suggests that Thea views critique as helpful, values input from her partner, and considers collaboration to be a resource at her disposal during the writing process.

Rather than relying fully on my own interpretations of student interactions, I also drew from students' self-reported experiences.

Anjeli: *Yes, I think the discussions help because it helped me think of more ideas and branch out.*

Ezra: *It's really helpful if you have more people critiquing the writing because then you can have a better influx of ideas and suggestions.*

Thea: *I agree with him on the feedback being one of the best parts. It was much easier to make a cohesive analogy with feedback.*

Across cases students used words like “ideas,” “suggestions,” and “feedback” to describe the pooling of knowledge resources occurring during collaborative and critical interactions. They also tied resources directly to their writing process, explaining that knowledge pooling was helpful or made analogy-writing easier.

Ezra: *I think that more collaboration would be really beneficial because the more people critiquing the analogy the more ideas you can add to make the analogy stronger and more effective.*

Here Ezra calls for even more collaboration, anticipating positive effects of more ideas on his product.

Engaging multiple perspectives

As students allowed their peers to view their ongoing writing process, this provided an additional lens through which evolving analogies could be examined. A change of perspective takes place when another individual views ones’ work and this change can reveal alternative interpretations or points of confusion. For example, one of Thea’s group members expressed confusion when reading her analogy for the first time. This additional perspective revealed an area in Thea's analogy where the reader could interpret her words in multiple ways.

Thea: *Energy in an ecosystem is like trying to pass water to someone with your hands. They are only going to get like 10% of that water. 90% of that water is on the floor now*

Toni[5]*:* *I think it should be without your hands instead of with your hands*

Thea: *Then you get 0% water what?*

Toni: *I thought you meant passing water in a cup with your hands not scooping it up sorry*

Thea: *Nah, just with your hands. eventually, someone down the line is getting drops of water*

In a revised version of her water analogy, Thea included an image of a person holding water in their hands. It is possible that this student's feedback resulted in Thea's decision to add an image to her analogy for clarity. Furthermore, Thea replaces the phrase "with your hands" to "with your bare hands." This may serve to emphasize that the person in the analogy is using only their hands and further resolve the confusion expressed by her group member early on in her process. Engaging the perspective of a collaborator allowed Thea to consider the effect of her analogy on an audience other than herself. She later reflects, “it was very helpful to have peer feedback, because they don't know what I'm thinking, so they're unbiased. I already knew what I was trying to say.” Beatrice and Grant also found engaging peer perspectives to be helpful.

Beatrice: *It was helpful to have a peer critique because you can see how others see your analogy.*

Grant: *It was helpful having a peer critique me because I got another ‘angle’ to see what my analogy looked like.*

[5] Toni only participated in one discussion before transferring to another campus, however I included this excerpt due to its significance for Thea, a focal student.

While collaboration allowed students to engage interpersonal perspectives, critiquing one's own analogy also provided a chance to engage multiple intrapersonal perspectives. Ezra engages the perspective of a hypothetical audience to consider what changes would make his analogy useful to “someone who doesn’t understand.”

Ezra: *I need to think about ways that I can connect these ideas to better understand and explain the process to someone who doesn't understand the basic concept. I need to find a way to weave my ideas together so that they make one cohesive analogy explaining what it is I am trying to convey.*

Aaron finds that his own perspective shifts day-to-day and engages his multiple perspectives to reevaluate his analogy at different points in time.

Aaron: *I think that looking at your analogy again after making it is helpful because you go into it with a different mindset on any different day. The first day you might go into being like my analogy is the best ever, but the next you might be like man this could be way better. Doing that you can often see mistakes you did not see before.*

Like Aaron, Grant reports that returning to his analogy multiple times allowed him to engage another perspective and, in turn, gain insight that supported him in (re)generating a better analogy.

Grant: *This seemed really helpful because rereading my own analogy, and just looking at it from a different perspective helped me see what I was doing wrong, or not doing wrong, but just seeing how I could do better on it.*

Imagining an audience, approaching their work over multiple days, and returning to their work multiple times were some ways that students could engage another perspective during the critique process even without a peer.

Testing explanatory power

Models (Lehrer & Schauble, 2000) and analogies (Treagust et al., 1998) are explanatory structures. When students cyclically evaluate models against the scientific concepts they are meant to explain, they receive feedback about how well their ideas are explaining the concept (Lehrer & Schauble, 2000). The explanatory power of a theory or a model is related to factual accuracy, precision, and detail (Ylikoski and Kuorikoski, 2021). During the writing process, students had multiple opportunities to test the explanatory power of their analogies through targeted critique designed to identify strengths and limitations. Based on Lakoff and Johnson's (1980) book *Metaphors We Live By*, a framework of *highlighting and hiding* was used to scaffold students' self and peer critique. Whether students used the *highlighting and hiding* language directly or adapted the framework to their own words, they utilized this tool to test out the extent to which an analogy could explain aspects of a scientific topic and where the analogical model breaks down. The *highlighting and highlighting* framework directed students' attention to how accurate, precise, and detailed their analogies were.

Independently, students closely examined their own analogies to identify aspects of the target concept that were highlighted in their analogy (explained by the analogy) and aspects that were hidden (not explained by the analogy). For Aaron, critique was useful in testing out the extent of his analogical comparisons and, in turn, finding out whether it conveyed what he intended.

Aaron: *I think overall this process [critique] was helpful because instead of just writing your analogy you had to really look into your analogy to see if you could actually compare it to things and see if it stood strong to what you intended it to do.*

By engaging in critique around analogical models, students evaluated ways in which the analogy comparisons do or do not explain the topic as intended. In many cases, this critical look revealed aspects that were hidden which gave way to a (re)generation of the analogy. In this way, several students found ways to increase the explanatory power of their analogies by highlighting previously hidden aspects of the target concept. The example below traces Thea's revisions to her analogy of energy in living systems.

Thea: *Energy in an ecosystem is like passing water down a line with your bare hands. The person at the start has a full handful. The next person is all going to get a fraction of that water. The last person will hardly get drops. This is like how each trophic level loses 90% of energy. At each pass, you'll only get about 10%.*

Thea: *It leaves out how much energy is falling into the environment*

Thea: *Energy is an ecosystem is like passing water down a line with your bare hands. The next person down the line will only get about 10% of that water. 90% of that water is going on the floor. This is similar to how we lose 90% of energy to the environment at each trophic level.*

In her self-critique, Thea pointed out that her analogy "leaves out how much energy is falling into the environment." She chooses to highlight this characteristic in her final regeneration, including that "90% of that water is going on the floor. This is similar to how we lose 90% of energy to the environment at each trophic level." By using critique to test the explanatory power of her analogical model, Thea was able to find an area that was unexplained and amend her model to explain the science concept more fully. Her (re)generation served to make her analogy more accurate, precise, and detailed (Ylikoski and Kuorikoski, 2021).

Collaboratively, students utilized the same strategies to test the explanatory power of an analogy for a new audience.

Aaron: *Matter in a metabolic process is like a machine designed to make something, you put in ingredients and you get a product, but it still consists of what you put in.*

Beatrice: *Your analogy hides the way matter is recycled and converted while decomposing and it highlights how matter is turned into mass. Maybe you could talk about a product that is recycled?*

Aaron: *Some items that you get out might be able to be used again, later on, if part of this product was like plastic for example then you could put in back in the process to be a reactant per say again*

Here, Beatrice tests Aaron's analogy, probing for limitations and identifying a characteristic of matter that is not explained in the analogy; the recycling of matter in subsequent metabolic reactions. Aaron applies this new knowledge to expand the explanatory power of his analogy by representing this concept in his analogy as a recyclable plastic that could become a reactant again.

Overall, students appeared to revise their analogies in response to their own self-critique as well as critique from others. In focus groups, they expressed appreciation for opportunities to "break down your own work" and connected these opportunities to perceived improvements in their analogical models.

Anjeli: *I like the [groups] because they help me see flaws or strengths in my analogy that I didn't notice.*

Aaron: *Being brutally honest in my opinion is a good thing because it helps to really know what the downfalls and the uprising of your work is*

Here Anjeli and Aaron agree that working collaboratively and receiving critique helped them better understand the strengths and limitations, or explanatory power, of their analogies.

Case Profiles

While facilitating cross-case analysis, I developed profiles of each pair of students to maintain a sense of each group's experience while examining trends across cases. Each case profile details shared practices within the collaborative pair that differ from other pairs as well as each student's unique approach to the work of analogy (re)generation.

Case 1: Thea and Ezra

For Thea and Ezra, self-critique played a role in their analogy (re)generation process but collaborative peer-critique was "the most important part." Both students felt that analogy writing was more difficult when the topic was *matter and energy in metabolic processes* (Cycle 2) than when the topic was *energy in living systems* (Cycle 1). They elaborated that this was in part because energy in living systems was an "easier" topic while the "complexity" of metabolic processes made analogy (re)generation more challenging. They also both reported that the extent of their collaboration during Cycle 2 was limited which is evidenced by less frequent message exchange between the two students during Cycle 2 than in Cycle 1. Thea and Ezra both expressed that more collaboration would have better supported them and increased the perceived quality of their analogies.

Though Thea and Ezra shared sentiments about the role of collaboration and critique, they differed in their approach to gauging their own success. Thea clearly attempted to explain aspects of the science topic within her analogy and made changes to her analogy with the intention of explaining more clearly or fully. Thea felt most successful during Cycle 1 because she thought that her analogy clearly explained the topic. Ezra, on the other hand, has the same intention but struggled to separate his ideas about success and creativity. His self-critique continually evaluated the creativity of his analogy and emphasized his desire to be more creative rather than the extent to which his analogy explained the target concept. In Cycle 1, Ezra abandoned his first analogy and generated an entirely new one on the basis that the first was "bad" because it was "not creative."

Case 2: Beatrice and Aaron

When asked about the role of collaboration in their writing process, Aaron and Beatrice shared a unique interpretation. Rather than reflecting on the exchange of ideas and critique as the other students tended to do, Aaron and Beatrice instead recognized exposure to multiple analogies as a form of collaboration. Both students explained that hearing and discussing other students' analogies helped them better understand the science topic. This is interesting in that it reflects these students' interpretation of collaboration as something that took place not only as they were writing but also during publishing, sharing, and continued sense-making.

For Beatrice and Aaron, critique seemed to serve distinct but equally valid roles in their analogy (re)generation process. Aaron regenerated his analogy several times with each updated version encompassing suggestions from peers as well as elements of his own self-critique. For Aaron, it appeared that identifying limitations in his analogy provided opportunities to adjust and extend his product. As Aaron regenerated his analogy, he encompassed more aspects of the science topic each time, attempting to represent the topic as fully as possible. Beatrice, on the other hand, chose not to make any changes to her analogy in either cycle. Instead, she wrote extensive self-critiques detailing the characteristics of the science topic that were and were not included. When asked to consider whether energy appears to be conserved in her Cycle 1 analogy, she re-stated that her analogy describes the importance of energy in living systems and explained that she would need to write an entirely new analogy to represent energy conservation.

Beatrice seems to have a firm grasp on the purpose of her analogy and the selective nature of analogies. This is reflected in her choice to make clear her intentions while being transparent about the limitations of her analogy. Additionally, she hints at the potential of multiple analogies to explain concepts that may not be simultaneously represented, which is a sophisticated understanding of the nature of analogical models.

Case 3: Anjeli and Grant

Anjeli and Grant engaged in a collaborative practice unique to their group. After presenting their analogies and exchanging critique, these students responded to each other with justification. They used language like “yes, but I wanted to focus on how different types of things have different types of energy” (Anjeli, discussion board) and “during that time I wasn't focused on representing the conservation of energy” (Grant, discussion board). This defending of their intentions allowed each of them to explain the choices they made and the limitations they accepted as part of their analogies. Though these two spontaneously included defense as part of their practice this may be a valuable activity that other students could benefit from as well. This also suggests a growing understanding of the nature of analogical models as selective rather than all-encompassing.

In combination with defending their choices, Anjeli and Grant made changes to their analogies in response to self and peer critique but approached changes using different strategies. As Anjeli discovered the limitations of her analogy, she generated a second analogy to complement the first. Rather than deleting her first analogy she presented both as a pair, allowing the second analogy to highlight a characteristic that was hidden in the first. In both cycles of this study, this dual-analogy strategy of responding to critique served to supplement her analogical model, therefore, increasing its capacity to explain the scientific concept. Like Aaron, Grant took a more traditional route of maintaining one analogy but adding to his writing as he critiqued his own work and received feedback from his partner.

Teacher Reflection

As is characteristic of action research, the researcher is considered to be part of the study. My role as a teacher-researcher, and subsequently participant-observer, allowed me to exist within the research and in a constant state of reflection. For this reason, I thought it relevant to include some of my thoughts regarding the case summaries.

As I reflect on these case descriptions, something that stands out clearly is the need to be intentional in the way science analogy writing is framed as a classroom activity. Ezra expressed understanding of analogies as tools for explanation, but he struggled with (re)generation because he was continually limited by his desire to prove his creativity. As a teacher, I could improve my framing of this activity by better explaining the goals and expected outcomes. I did not intend for students to interpret this type of learning as an exercise in creativity for the sake of being creative. Though creativity is an element that should be acknowledged, what is most important is that students work toward creating tools that can be used to explain the science topic. Creativity, then, should be framed as a skill that is exercised in the pursuit of functional and useful models.

A second take-away across cases is the need to leave multiple options open as students take up these new practices. Cases 2 and 3 suggest that there are many ways for students to use the knowledge of their writing that they gain through critique and collaboration. Both Aaron's continuous revision method and Beatrice's acceptance with transparency are consistent with the ways in which models might be negotiated in the sciences and therefore are equally valid. Similarly, Anjeli's addition of a second model serves the same end as Grant's additive strategy. Scientists who work with models revise them, address their selectivity, combine them with other models, and add to them. There are many ways to interact with models, physical or analogical, and it is important that students are not limited to a rigid linear process. This requires that learning activities are designed with flexibility, instructions are left open to an array of possibilities, and students are empowered to pursue their own strategies.

Finally, I noticed that several students reached a point of saturation where they felt their analogy could no longer be revised. They addressed limitations of their analogies in their self-critique and some even attempted to resolve this tension by explaining their choice to limit the analogy to something they wanted to focus on. I interpret this as a reflection of their understanding of models as inherently limited and a step toward acknowledgement that all analogies break down. This is another aspect that students must negotiate as they generate analogies. No analogy can perfectly represent a target concept and it is up to the students to decide when their analogy is satisfactory. Explicit conversation about this saturation point may have further teased out this important aspect of the nature of analogical models and I may have missed an opportunity to engage my students in discussion around this moment of saturation.

Negative Case

Yin (2014) encourages the thorough exploration of all data, including negative or contradictory data, as a way of establishing a more holistic view of the data set. One student, Thea, reported an experience that differed substantially from her classmates. She reported that she already understood energy in living systems very well and did not learn anything new during Cycle 1. In Cycle 2 she became very confused and gave the following report:

> *Thea:* *I found writing an analogy for this topic very difficult. My ideas were either too similar to the actual process or it just didn't make sense. I don't think this helped me understand the topic. If anything, it just made me confused for a few days. My first analogy was much easier to write because it was an easier topic for me.*

One interpretation of this negative case is that there may be an optimal point during the learning process where analogy generation can be most effective. When Thea fully understood the topic, she felt that there was no new learning occurring and when she struggled with the topic too much, she found analogy writing confusing. Perhaps there is an ideal point where foundational knowledge has been established, allowing students a sufficient base from which to continue the construction of new knowledge. This is consistent with Kaufman et al.'s (1996) suggestion that "in order to be able to create meaningful analogies, students would need to have an adequate knowledge of the target domain prior to the exercise" (as cited in Haglund, 2013, p. 47). This is also consistent with Orgill & Bodner's (2004) findings that students thought analogies were least useful when topics were already well understood and when topics were overwhelming. Orgill & Bodner's study was with university-level biochemistry students and studied teacher analogies rather than student-generated analogies. More research is needed to determine when analogies are useful or not useful in K-12 science education and whether certain topics are more appropriate than others for analogical learning.

Discussion

This paper presents an argument for further exploring collaboration and critique as classroom supports for science students as they (re)generate science analogies. The results of this study provide evidence for two key findings summarized below.

Finding #1

Collaboration and critique support analogy (re)generation by allowing students to pool knowledge resources, engage multiple perspectives, and test the explanatory power of their analogies. All students generated functional analogies during Cycle 1 and Cycle 2. Functionality was determined by whether the analogy (1) drew a comparison between the science concept to another entity and (2) explained at least one characteristic of energy or matter. No students failed at the task (did not generate an analogy or generated an analogy that did not explain any characteristics of the target science concept). Schamp (1990) would add that "any model is satisfactory, as long as it fits the facts we are using to test it" (p. 16). For this reason, I consider all models included in this study to be satisfactory as all of them fit the scientific concepts the student had chosen to convey. This suggests that middle school students are capable of constructing analogies given the appropriate amount of support, for instance, through a process of analogy (re)generation like the one described in this work.

In the context of this study, support was provided through interactions with peers as well as scaffolded opportunities to apply and exchange critique. There is substantial evidence of students returning to their products and (re)generating their analogies in ways that expanded what could be explained by the analogy. This serves as a compelling indication that students were supported in the process of analogy (re)generation. Additionally, all six focal students consistently reported that interacting with peers and exchanging critique were helpful during the analogy (re)generation process. Getting new ideas, getting another perspective, and receiving feedback were most widely recognized by students as supportive factors.

Analysis of discussions and focus groups revealed grounded themes that describe three ways that collaboration and critique function together to support student analogy (re)generation. Students bring a wide range of knowledge and experience to the classroom. These funds of knowledge (Moje et al., 2004) play a critical role in the knowledge construction process, especially within an instructional approach that recognizes and builds on students' knowledge and experiences. Analogy generation requires students to construct a conceptual bridge between a familiar source concept drawn from their everyday lives and a new science concept to be learned through a network of comparisons. It follows then that students with more varied funds of knowledge would have a wider pool of source domains to draw from. By interacting with others, students expand their pool of knowledge resources which broadens the range of source domains any one student can access. There were several instances of students suggesting a comparison that could fit within the wider context of a peer's analogy, effectively adding to the pool of knowledge resources that student might use to construct a science analogy. Students even solicited such suggestions from each other and acknowledged the value of such "ideas" and "suggestions" in their focus groups.

Generating an analogy is a challenging task (Harrison & Treagust, 2006; Treagust et al. 1998; Zook, 1991). Models are easier to understand when they are literal (Lehrer & Schable, 2012) but the capacity of literal models is limited, especially in the context of highly abstract concepts such as matter and energy in biological systems. This necessitates the use of abstract models like analogy and, in turn, the acceptance of a higher cognitive load to use a model that is better suited for developing sophisticated understanding (Harrison & Treagust, 2000). To mediate the level of challenge, students could reach out to each other when they struggled and learn from other students' approaches to the task. The data showed students asking for input from peers at multiple stages before publishing a finished product and reporting that they valued peer interactions. From a cognitive perspective, the support of peers should allow students to operate within their Zone of Proximal Development (Vygotsky, 1962) and accomplish more than they may be able to do in isolation. Similarly, social interaction allowed students to engage the perspective of others to explore alternative interpretations of their written analogies. Students reported that peers provided them with "another angle" from which to view their work which, on several occasions, prompted students to revise their analogy for more clarity. This negotiation is an important social resource gained from interaction in the classroom community (Harrison & Treagust, 2000).

Research on analogies in science strongly emphasizes the need to examine the limitations of analogies (Aubusson et al., 2006; Coll, 2006; Schamp, 1990). This is comparable to the way any model would be tested in the scientific community to determine where it breaks down and what this reveals about the collective scientific understanding of a phenomenon. Haglund (2013) adds that "learning happens in the analysis of analogy breakdown and it is up to the teachers to make sure that such analysis is carried through" (p. 60). By critiquing their own analogies and collaboratively exchanging critiques between peers, students were able to test the explanatory power of their analogies, revealing what could be explained and what could not be explained. As expected, students found that their analogies obscured characteristics of the target concepts, but it is in this space that students were pushed to resolve some of these tensions. Through multiple rounds of (re)generation and further testing through critique, students produced more comprehensive versions of their analogies that were more accurate, precise, and detailed. During this process, students appeared to construct new scientific knowledge and reported deeper scientific understandings. Like other models, analogies have generative potential but ideal analogies that quickly give way to understanding, such as those provided by textbooks or teachers, are not being constructed and would be unlikely to generate new knowledge. Rather, "conceptual growth emerges from continual refinement and synthesis of fragmented, incomplete knowledge" (Wong, 1993, pp. 1259-1260). This study provided evidence that collaboration and critique allowed students to test the explanatory power of their analogies. This, in turn, gave students cause to continually refine and synthesize their knowledge, slowly knitting fragments of understanding together.

Finding #2

Collaboration and critique supported analogy (re)generation as a generative process rather than a static product. Modeling has most recently been conceptualized as a scientific skill which must be practiced and can improve over time; a process rather than a product (Lehrer & Schauble, 2012; Schwarz et al., 2009). This thinking has also been extended to analogies (Harrison & Treagust, 2000; Treagust et al., 1998; Wong, 1993). In the context of this study, student reflections and feedback positioned analogy-writing as a process that becomes easier over time with repetition. When asked about how Cycle 2 felt similar or different from Cycle 1 students mostly commented on their degree of comfort. Grant felt more confident in himself the second time he generated a science analogy. Ezra also felt that he had a better understanding of how to write analogies. Aaron captured this same sentiment in a way that stuck with me; “It was quicker this time and I am getting better. We talked in our small groups more. I think we are getting more accommodated to analogy-ing" (Aaron, field notes). I felt that Aaron’s unique term *analogy-ing* captures the way in which students conceptualized their work with analogies as a practice rather than a product.

This study also suggests that when students (re)generate analogies, the analogies take on a dynamic quality and function as a space for students to generate new knowledge. Several students reported that the process of analogy writing helped them understand the science topic.

Beatrice: *I think having to think about my analogy helped me better understand the science topic.*

Aaron: *I think that it [analogy writing] has made me understand the science topic a bit more because of all the ways different people look at it.*

Anjeli: *This activity definitely helped me see the process of cellular respiration and photosynthesis and get a better understanding by visualizing it better.*

Grant: *One thing that helped me better understand the concept is that I understand that photosynthesis and cellular respiration is just a never ending cycle.* (Grant compared matter cycling to recycling aluminum cans)

Overall, most students’ reflections conveyed that their analogies were not demonstrations of their knowledge so much as activities that lead to new knowledge or deeper understanding.

It should be addressed that this study lacks the structure to suggest a direct causal relationship between the collaboration and critique integrated with analogy (re)generation; however, the student experience within the context of a collaborative and critical learning environment is noteworthy and may be a fruitful area of further research. Students' perceptions of analogy generation as a process that they have practiced and improved as well as their reports of achieving new understanding during the analogy activities suggest that, in this collaborative and critical space, students may come to better understand the role of analogical models in the scientific endeavor.

Future Directions

This study does not seek to defend a claim so much as to raise questions and alternative considerations. One such possibility is that problems associated with using analogies as tools for science learning lie not in the nature of analogies but in their execution. Previous studies have primarily positioned student analogies as forms of assessment (Lancor, 2013, 2014; Pittman, 1999). This one-and-done approach offer no chances for analogies to be negotiated and revised which increases the likelihood that they will be misinterpreted or overextended, leading to misconceptions. This study yielded evidence that leveraging collaboration and critique may better position analogy-ing as a practice rather than analogies as illustrative products or demonstrations of learning. In the context of this study, analogy (re)generation was shown to be a cyclical activity, as it is thought to be (Wong, 1993) but has not previously been implemented in classroom-based research.

This adds to the body of research on student-generated analogies, collaborative analogy generation, and student critique of analogies in school science. This study also presents an exemplary classroom approach that may serve as a springboard for new ideas and instructional strategies that integrate analogies into science education in ways that are consistent with the practices of scientists. Furthermore, this study raises several more questions worthy of pursuit.

- To what extent can analogies function like models in the science classroom and in what ways do analogy-ing and modeling differ?
- What nuances exist between analogy-ing and modeling in the field of science and how should these translate to classrooms?
- Can collaboration and critique within analogy writing be studied separately and, if so, to what degree do they influence student learning independently?

Finally, the topics chosen for the analogy activites in this study were *energy in living systems* and *matter and energy in metabolic processes*. Though these science topics are specific to biology, matter and energy are cross-cutting concepts (NGSS Lead State, 2013) that transcend multiple scientific disciplines including physics and chemistry. For this reason, the findings warrant further exploration of analogy (re)generation across a variety of science classes.

Practitioner Implications

This study took place during a global pandemic in which strict safety protocols prevented students from being in close physical proximity. Some students were present in the classroom while others remained at home, attending class virtually. Even students in the classroom were isolated by social distancing. Further safety measures limited the types of activities that normally take place in science classrooms. Reallocation of budgetary resources toward health products such as masks and sanitizing stations left little funding for learning materials and science classrooms were discouraged from implementing hands-on activities that required students to touch or share materials. For these reasons, traditional modeling was near impossible to implement. Collaborative and critical analogy (re)generation presented itself as an alternative that required no materials and could be conducted in-person and virtually. This has implications as a practical option for current classrooms affected by the COVID-19 pandemic as well as classrooms with limited resources and for science distance learning.

An important consideration for teachers is the framing of analogy writing activities. Implementation of such activities should be in line with the ways in which analogies are used by scientists. This is not a classroom activity intended simply to spark creativity or increase engagement by introducing novelty (thought it might). The goal or analogy writing is to produce something that can explain a phenomenon and to facilitate thinking about that phenomenon.

> As researchers or teachers, we generate post-festum analogies when we have the required background knowledge and want to convey particular aspects of a domain to others, such as students, our colleagues or the general public. In contrast, generation of heuristic analogies refers to the process where we use analogies to explore the connection between domains of which we only have limited prior knowledge. This kind of cognitive processing may be used when conducting research, but also by students, both when interpreting teacher-generated analogies or exploring their own self-generated analogies.
>
> (Haglund, 2013, p. 51)

While students are not adding to the knowledge base of what is known and unknown in science, they can mirror this process to add to their own knowledge base. In this way, they embody a practice and way of knowing that is specific to science. Analogies should also be framed as dynamic rather than static which means that students should iteratively evaluate and refine analogies. This can happen in many different ways and should be a divergent rather than convergent process. Students in this study approached revision in multiple equally valid ways.

Limitations

The limitations of this research stem primarily from the nature of school research with young people and characteristics of the naturalistic setting. First, member checking is the practice of inviting participants to examine the researcher’s preliminary analyses and comment on the accuracy or credibility of the researcher’s interpretations. Member checking is often used in qualitative research, however, due to the age of my students (13-14 years old) and ethical concerns regarding contacting a minor outside of school context, member checks were not conducted for this study.

Second, these students are part of a small cohort of academically accelerated middle school students enrolled in a Pre-AP biology class. A caveat to my findings is the small sample size on which my claims are based. The atypical age and relative academic success of these students is also not representative of all biology classrooms, reducing the potential to generalize findings to other situations. The student cohort takes advanced math and science courses together over three years. The intimate setting of the biology class as well as the history between these students results in a level of comfort with collaboration that may not be present in other classroom settings. Additionally, the research takes place on a campus where collaboration and critique are encouraged and occur frequently in all class subjects. This may also affect students' comfort level with collaboration and critique which is not representative of typical biology classrooms. Future research in more generalizable settings and with larger participant pools would continue to grow this body of research.

Finally, it should be noted that findings related to students’ success in generating functional analogies and support for student during this process are based on my perceptions as an observer and students reports of their own perceptions. The subjective nature of findings based on perception is a limitation of this research. It was not the goal of this study to objectively evaluate the degree to which students' analogies were scientifically accurate or to compare students' analogy products; however, the development of such a tool could benefit this area of research. I do not consider my small sample (n=6) sufficient for developing such a tool but a larger-scale study has the potential to design such an instrument.

Conclusion

Having begun this work with an anecdote, I will also end with one. Several months after the conclusion of this study the biology students were tasked with end-of-year inquiry projects. Without prompting, several participants strategically used analogy to summarize and convey their research. To explain how GMO crops can produce compounds toxic to insects but safe to humans, Aaron compared this relationship to chocolate's toxicity to dogs.

> *At first sight, a plant that produces a poison might seem bad, but what is poison to one creature is harmless to another. Take chocolate. You probably eat chocolate, but your dog can't eat chocolate. You might eat that poison on the plant and feel fine, but that bug… it dead.* (Aaron, field notes)

Beatrice also used an analogy to explain the potential repercussions of technology advancement.

> *Our final message can be best described by Newton's third law: every action has an equal and opposite reaction. The advancement of technology can be a great thing but in the wrong hands, it could throw everything out of order*. (Beatrice, field notes)

Schwarz et al. (2009) identified spontaneous use of models as a marker of the most sophisticated level of modeling practice. This spontaneous use of analogy struck me as compelling evidence of my students taking up the practice of analogy-ing and making it their own.

This study found that collaboration and critique supported student analogy (re)generation in multiple ways and that these factors function together in ways that are consistent with analogy-writing as a generative scientific process. Though the body of research surrounding analogies in science education is large, there appears to be a drop-off of interest in recent years. With renewed national curricular focus on modeling practices, there is potential for science classrooms to explore analogy (re)generation as another way of embodying the practices and intellectual tools that produce scientific knowledge. Whether analogy (re)generation, or analogy-ing, should be considered a form of modeling or a practice of its own is unknown but may be a fruitful area of further research.

There is an abundance of territory left unexplored regarding the potential of analogies in science classrooms. I share the enthusiasm of Harrison and Treagust’s (2000) words: "the scope and application of analogical models in thinking and working scientifically seems limited only by the modeler’s purpose and creativity" (p. 1012). It is my hope that this small contribution to the field spurs new conversations and pedagogical innovations regarding the scientific practice of analogy-ing.

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APPENDICES

Appendix A

Field Note Instrument

Indicators	Descriptive Field Notes	Reflective Field Notes
Group 1 Students: 1A 1B 1C		
Group 2 Students: 2A 2B 2C		
Group 3 Students: 3A 3B 3C		
Group 4 Students: 4A 4B		

Appendix B

Focus Group Protocol: Cycle 1

Welcome to our focus group conversation. Today we will be discussing your experience with creating analogies in your biology class. Your thoughts and feedback will help your teacher make adjustments for the next time you create an analogy as part of a science activity. I want to know what parts of the process were helpful and what parts were challenging so honesty is key. You will certainly not hurt my feelings. I have planned this interview to last no longer than 15 minutes. During this time, there are a few norms we should follow in order to make sure everyone is heard.

- *There are no right or wrong answers, only different points of view.*
- *I am here to facilitate the discussion so I will only ask questions.*
- *Address the whole group.*
- *You don't need to agree with others, but please disagree respectfully.*
- *You can use pronouns (I, you, him, her) but please avoid typing your classmates' names. This will help protect everyone's privacy.*

We will start with the first question.

1. In your biology class, you wrote your own analogy to compare our target science topic to something outside of science that you are more familiar with. This is possibly something you have not experienced in science class before. What was this experience like for you?

Probe: Was there any part of this activity that you found challenging or difficult? What part?

Probe: Was there any part of this activity that helped you better understand the science topic?

Probe: What would you change if we were to try this process again with a new topic?

2. During the process, you had opportunities to discuss your analogy with classmates before finalizing your analogy. Would you want to include this type of discussion the next time you create an analogy? Why or why not?

Probe: Is there anything you would change about the way our discussions worked?

Probe: Would you prefer to collaborate more, less or the same amount next time?

3. You also critically analyzed your analogy. You mapped out similarities and differences, looked for limits, and you may have revised your analogy. Did any part of this process feel useful or helpful to you? Why or why not?

Probe: Is there anything you would change about this critique component?

Probe: Was it helpful to have a peer critique your analogy as well? Why or why not?

This concludes our focus group. I appreciate you taking the time to talk to me. You've given me so much to think about and helped shine light on my research questions. I am grateful for this experience to improve as a researcher.

Post-Session Comments and/or Observations:

Focus Group Protocol: Cycle 2

Welcome to our focus group conversation. Today we will be discussing your experience with creating analogies in your biology class. Your thoughts and feedback will help your teacher make adjustments for the next time you create an analogy as part of a science activity. I want to know what parts of the process were helpful and what parts were challenging so honesty is key. You will certainly not hurt my feelings. I have planned this interview to last no longer than 15 *minutes. During this time, there are a few norms we should follow in order to make sure everyone is heard.*

- *There are no right or wrong answers, only different points of view.*
- *I am here to facilitate the discussion so I will only ask questions.*
- *Address the whole group.*
- *You don't need to agree with others, but please disagree respectfully.*
- *You can use pronouns (I, you, him, her) but please avoid typing your classmates names. This will help protect everyone's privacy.*

We will start with the first question.

1. In your biology class, you wrote your own analogy to compare matter in metabolic processes to something outside of science that you are more familiar with. You have experienced a similar activity in biology class before. What was this experience like for you this time?

Probe: Was there any part of this activity that you found challenging or difficult? What part?

Probe: Was there any part of this activity that helped you better understand the science topic?

Probe: How did this experience compare to our first analogy writing activity (energy in ecosystems)?

2. During the process, you had opportunities to discuss your analogy with classmates before finalizing your analogy. Would you want to include this type of discussion the next time you create an analogy? Why or why not?

Probe: Is there anything you would change about the way our discussions worked?

Probe: Would you prefer to collaborate more, less or the same amount next time?

3. You also critically analyzed your analogy. You mapped out similarities and differences, looked for limits, and you may have revised your analogy. Did any part of this process feel useful or helpful to you? Why or why not?

Probe: Is there anything you would change about this critique component?

Probe: Was it helpful to have a peer critique your analogy as well? Why or why not?

This concludes our focus group. I appreciate you taking the time to talk to me. You've given me so much to think about and helped shine light on my research questions. I am grateful for this experience to improve as a researcher.

Post-Session Comments and/or Observations:

Appendix C

Student Analogy Guide

Adapted (with permission) from Lancor, R. A. (2014). Using student-generated analogies to investigate conceptions of energy: A multidisciplinary study. *International Journal of Science Education*, *36*(1), 1-23.

I. Write Your Analogy

Write your own analogy describing *energy flow in living systems* / *matter or energy in metabolic processes*. Be creative! The more connections you are able to make, the stronger your analogy becomes.

Your analogy:

Explain the analogy here: [this document will be digital so students can expand the space to fit their writing and any supplementary illustrations]

II. Map Out Your Analogy

Now you will evaluate your analogy. Consider what aspects of it are shared with the target concept and which aspects are different. All analogies break down at some point; the trick is to figure out where. (You are allowed to modify your original analogy if necessary as you evaluate it.)

What similarities are there between the old idea you are already familiar with and the new concept you are trying to learn? Use the table to list both structural similarities (features that look the same) and functional similarities (features that function in the same way). For example, in the planetary model of the atom the sun plays the role of the nucleus. Both are in the center of the system so this is a structural characteristic.

Feature of Target Science Concept	**Feature of Analogy**	**Shared Characteristic**

III. Critique Your Analogy

<u>Highlighting:</u> What aspects of the target science concept does it represent well? These are strengths of the analogy.

<u>Hiding/Limits:</u> There are limits to every analogy. What differences are there between the analogy and the target science concept? In the example above, one obvious difference is that the sun is much, much larger than the nucleus of an atom. The planetary model of the atom *hides* the true size of the nucleus. Also, think about what aspects of the target science concept are not represented by the analogy. What is left out?

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