

Use of hands-on classroom experiments as physical analogies in student discussion

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Models are commonly used in astronomy education to help students understand and discuss difficult or abstract concepts. From a physics education research perspective, metaphors and analogies are often used to support reasoning about abstract phenomena. This study investigates how students draw on classroom experiments as physical analogies (a multimodal instance of conceptual metaphor) when reasoning about exoplanetary atmospheres. We conducted two lessons: one about cloud formation on Earth and exoplanets and another about lightning on Earth and exoplanets, both including a hands-on experiment related to the topic. The students were then split into peer-led focus groups and tasked with discussing the experiment and its relation to weather in planetary atmospheres. We audio-recorded these group discussions and extracted relevant excerpts. We analyzed these excerpts sequentially using thematic analysis, network analysis, and conceptual blend analysis. We identified four input spaces used by students (relevant physics, the experiment, Earth conditions, and exoplanet conditions) and three ways in which students use analogies (mapping between domains, identifying limitations, and extending the analogy). Across these analyses, we found that students integrate these input spaces to construct blend spaces that mediate their reasoning about processes and concepts in Earth and exoplanetary weather phenomena. We also discuss implications for future research and teaching.

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I. INTRODUCTION

In science learning, models help convey and discuss abstract concepts by comparing them to something more tangible or familiar [1]. Metaphors and analogies can serve as models to help students understand and act within the

context of science education [2]. In astronomy education, research into the use of metaphors and analogies as models has focused on verbal or visual aspects [3]. However, it is also possible for these models to be enacted physically [4,5].

Using experiments as analogies in astronomy teaching and learning situations allows students to gain hands-on experience with astronomical phenomena with which they would otherwise be unable to interact [2]. Examples of such analogies are the stretched rubber sheet representing spacetime [6], a balloon with stickers stuck to it representing the expanding universe [7], or the movement of vehicles representing redshift [8]. These examples show that astronomy educators often use everyday objects and

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phenomena to create hands-on experiences to help students access abstract astronomy-related ideas and concepts.

In this study, we expand on this idea by investigating experiments as analogies that can be used by students to understand and discuss phenomena that are relevant to contemporary astrophysics, specifically weather phenomena on exoplanets. Weather phenomena, such as cloud and lightning formation, form interesting cases because, on the one hand, they are well-known phenomena from students' everyday experiences, and, on the other, they are relevant to contemporary astrophysics research [9–11]. Still, students cannot directly observe or measure the atmospheres of exoplanets. Hands-on experiments that replicate key physical processes, such as the formation of clouds and lightning, may provide opportunities for students to learn the characteristics of these processes and to relate these characteristics to exoplanet research. In doing so, we argue that experiments as analogies provide a possible bridge between hands-on experience and theoretical conceptualizations.

Many common analogies in astronomy education are primarily shown through videos, textbooks, or thought experiments [5,7]. While these approaches can be valuable, they often position students as passive recipients of information rather than active participants in knowledge construction. They do not allow students to explore and test the limitations of the models, while inquiry-based, hands-on approaches are designed for students' active construction and reflection [12]. In this study, we therefore investigate how students make use of hands-on experiments as physical interactive analogies. Here, students manipulate experiments autonomously to learn more about the phenomena to which these experiments are analogous. While literature has investigated how students can use hands-on experiments to learn scientific concepts [13], empirical studies investigating how students may use hands-on models as analogies in astronomy education are lacking [2].

We are particularly interested in how students can make use of analogies after engaging in hands-on experiences. In other words, we are interested in how students' understanding of the analogies that they employ extends beyond the immediate physical interaction in the classroom. Our goal with this study was to investigate an educational phenomenon that entails how students articulate, interpret, and connect knowledge from scientific experiments to the target scientific concept.

To investigate this phenomenon, we have made use of peer-led discussions. While peer-led learning is a well-established practice in STEM education [14], its use as a structured approach for focus groups and discussions in research remains largely unexplored. Peer-led discussions have been utilized for data gathering in other fields [15], but this approach has not yet been widely applied in STEM education research. This study addresses these methodological gaps. By integrating hands-on experiments in the lesson and peer-led discussions afterward, we aimed to give

the students in this study greater agency in both their engagement with lesson content and their reflective discussions. Our intention with this strategy was to collect data that would be valuable in a detailed analysis of students' use of hands-on experiments as analogies. Although the empirical setting is astronomy education, the study is situated within physics education research, focusing on students' analogical reasoning and conceptual blending.

II. THEORETICAL BACKGROUND

A. Conceptual metaphor

In this study, we consider in-class experiments as physical analogies [16]. Analogies work through mapping aspects of elements of a simple, accessible “base domain” onto a more abstract “target domain” [17]. For example, in the analogy of “life is a highway,” the base domain is the highway—a thing that people have experienced and understand. The target domain is “life”—a more abstract subject that we wish to understand better through this analogy. In educational analogies, the base domain consists of experiences and ideas that students are thought to have access to already, and the target domain is the more abstract content that we wish the students to be able to understand [17]. By making the links between the two, the goal is to aid students in their understanding of the target domain [16].

A common example of an educational analogy in astronomy is the rubber sheet analogy for the curving of spacetime [5,18]. In this analogy, the curvature of spacetime is demonstrated through the use of a large rubber sheet, and objects are dropped onto it to demonstrate the curvature and its effects [18, Sec. 4]. The target domain is gravitation and spacetime, and the base domain is the rubber sheet. The successful application of the metaphor relies on students' knowledge about how rubber sheets work, as well as the teaching and learning situation that helps students make the intended metaphorical mappings between the rubber sheet and gravity and spacetime [6]. For instance, the fact that objects can bounce off the rubber sheet is irrelevant to the analogy, while the fact that a massive object will stretch and contort the rubber sheet is essential. It is crucial that the teaching and learning situation provides students with opportunities to discern these differences.

Usually, base and target domains are determined from linguistic or contextual clues. Contextual cues could be gestures [19] or intrinsic to the task, for example, asking students to understand heat in terms of marbles [20]. In many cases, the structure *target is like base* is used. For example, the electricity (target) *flows like* water (base). We would not expect the opposite: water flows like electricity, if we assume that water resides in a base domain and electricity in a target domain. Students' access to the target domain then relies on their understanding of the base domain.

In this study, the intended base domains were the experiments. In one experiment, “cloud in a jar,” students

investigated the conditions under which water vapor will condense around possible nucleation agents. In the other, “lightning sparks,” students experimented with the triboelectric effect to produce a visible electric discharge. The intended target domains were the corresponding exoplanet and Earth weather phenomena, cloud and lightning formation. The experiments are described in more detail in Sec. III. The intention is for students to connect corresponding elements in base and target domains, but this is not necessarily a straightforward process [17], particularly in the case of the lightning experiment. Previous research suggests that students will likely need to construct intermediate conceptual structures [21,22] to aid them in making mappings. To conceptualize such structures, we turn to conceptual blending theory.

B. Conceptual blending

Conceptual blending [23] is a framework related to conceptual metaphor theory. Where conceptual metaphor theory uses two domains, conceptual blending integrates multiple mental spaces to generate new meanings, ideas, or insights. Figure 1 shows the basic structure used in conceptual blending.

In the basic model of Fauconnier and Turner [23], a conceptual blend is made from two input spaces that draw from one generic space. Elements of these two input spaces are then selected to be pulled into a blend space, depending on the purpose and context of the blend that is being created. The blend space can then be used to generate new information. Podolefsky and Finkelstein [17] use the conceptual blending example of the solar system and an atom, as seen in Fig. 2. One input space is the solar system. It includes elements such as planets revolving around the Sun, the Sun attracting the planets, and the Sun being yellow. In the other input space is the atom: there is a

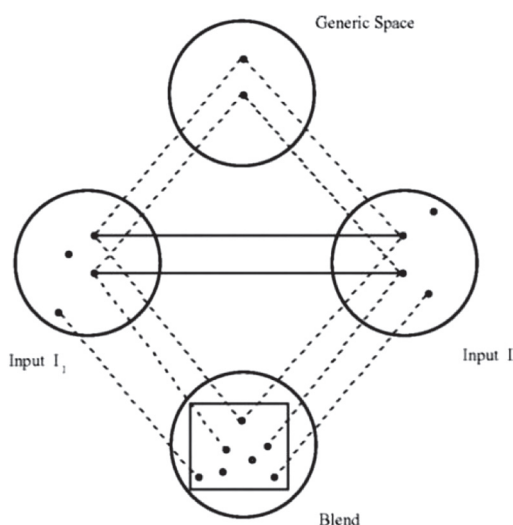


FIG. 1. A diagram showing the basic structure of a conceptual blend [23].

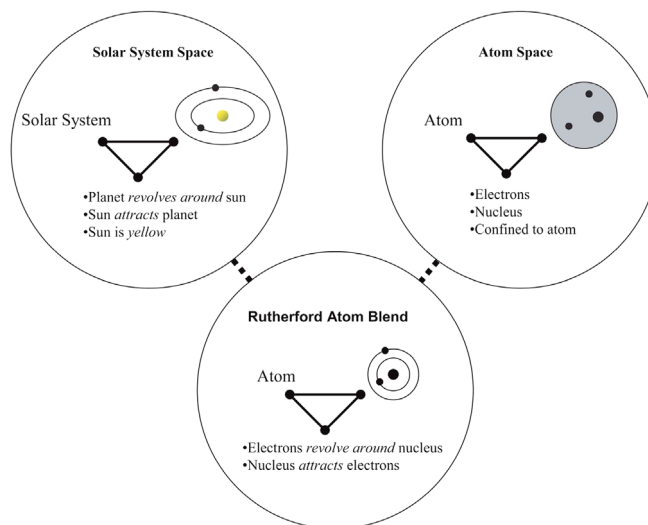


FIG. 2. An example of a conceptual blend [17].

nucleus, there are electrons, and they are confined to an atom. The relevant elements of these spaces are projected into the blend space, resulting in a description of the Rutherford atomic model: electrons revolve around the nucleus, and the nucleus attracts the electrons. In this blended space, we can use the input space of the solar system to help us provide a new understanding of the atom as compared to the input atom space.

According to Fauconnier and Turner [23], conceptual blends are ubiquitous in human thinking. Thus, the example above can be seen as a historical explanation of how a particular model is a conceptual blend of two other models. Podolefsky and Finkelstein [17] proceed to construct *intended* blends for students to create as part of instruction through analogical scaffolding.

Even if conceptual blends are ubiquitous, existing applications of conceptual blending theory in physics education research have tended to focus on individual reasoning and on verbal, visual, or symbolic representational inputs [17,24–26].

In this study, we focus on the conceptual blends that students can be observed to construct during peer-led discussions anchored in a shared hands-on experience. We examine how these blends emerge, develop, and are reconfigured over time in students’ joint reasoning. Conceptual blending theory is therefore used as the primary analytic framework, as it affords analysis of multiple input spaces, emergent blend structures, and the dynamic development of analogies in peer interaction. The blend spaces we identify are not end goals of learning but temporary and dynamic structures that mediate the mapping between source and target domains.

This makes them different from bridging analogies [21], which can be seen as carefully planned stepping stones that help students gradually connect an intuitive idea to a more abstract scientific concept by introducing an intermediate

familiar scenario that shares structural similarities with both. In contrast, the conceptual blends that students constructed in our study are not planned in advance and may change rapidly during discussion.

Our conceptual blends are also related to Vosniadou and Brewer's [22] synthetic models, which are understood as intermediate constructions that integrate intuitive and scientific ideas during learning. A key difference, however, lies in the temporal scale at which these constructs are analyzed. Synthetic models are typically described as relatively stable intermediate models that can persist over extended periods of learning, whereas the blend spaces we identify are transient and dynamically reconfigured during ongoing peer interaction. In this sense, both can be seen as intermediate structures, but they capture different moments in the process of conceptual change.

With this study, we investigated the temporary and dynamic blend spaces that students construct when mapping the source-input domain of a hands-on experiment to a target-input domain during peer-led discussions, with particular attention to their collective, materially grounded, and temporally evolving character.

C. Research question

The general question that this paper addresses is exploratory: How can upper secondary students use experiments about cloud and lightning formation as analogies during peer-led discussions that take place after a hands-on lesson? The methodological aim of the paper is to contribute to the development of theory in physics education research by analyzing novel empirical data, i.e., from peer-led student discussions after a lesson.

To add structure and guidance to our general question, we have broken this broader question down into subquestions.

- RQ1: Which input spaces do students use as base and target domains in the analogies of the cloud and lightning formation lessons?
- RQ2: What kind of analogical mapping processes can be identified during postlesson peer-led discussion?

- RQ3: What characterizes the blend spaces that can be identified in these postlesson discussions?

These research questions are addressed through an analysis of peer-led discussions following hands-on experimentation, using conceptual blending theory as the primary analytic framework. We employ a qualitative-dominant mixed-methods design employing a conversion (quantitizing) approach [27], in which qualitative discourse data were systematically coded and transformed into quantitative representations for analytic purposes.

Following Leech and Onwuegbuzie's [27] typology, the present study can be characterized as a qualitative-dominant, partially mixed, sequential design, involving iterative movement between qualitative analysis, quantitative representation of coded data through network analysis, and subsequent qualitative interpretation. The use of network analysis allows us to examine relational patterns among codes and analytic categories, thereby supporting the identification of structural regularities in the data [28]. We argue that this analytic approach is consistent with the underlying theories of analogy, metaphor, and conceptual blending, which emphasize relational structure and connections across domains.

We have structured this article as follows. The next section provides a brief description of the lessons used in this study. The methods section then describes our data collection, which involved first conducting the lessons and then collecting audio recordings from peer-led discussions. The analysis section outlines how we identified excerpts, how and why we used thematic analysis and network analysis to find and represent connections between analogy-relevant categories, and how we conducted a conceptual blend analysis on selected excerpts. Following the results of these analyses, we discuss how our findings address our research questions and then outline the limitations, implications for teaching, and potential directions for further research.

III. THE EXPERIMENTS USED IN THIS STUDY

In this study, we used two experiments, one for each lesson. The first [29] concerns cloud formation, and the

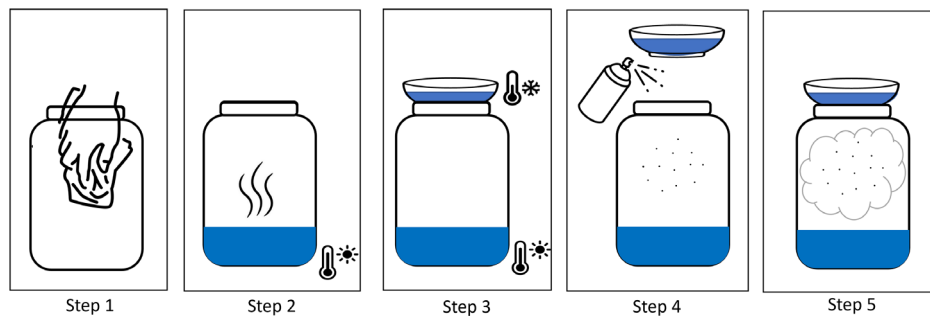


FIG. 3. Each step of the cloud formation experiment [29]. Step 1: the inside of the clean jar is coated with a very thin layer of dish soap. Step 2: hot water is added. Step 3: a bowl of ice water is put on top. Step 4: a small amount of hairspray is added. Step 5: a cloud forms.

	Experiment	Planet Atmosphere
Evaporation		
Super Saturation		
Aerosol		
Cloud Formation		

FIG. 4. A mapping of each stage of the cloud experiment to each stage of cloud formation on a planet [29].

second [30] concerns lightning. These experiments were developed in collaboration with exoplanet scientists from the CHAMELEON network [31], a research network focused on cloud formation and lightning in exoplanet climates. The clouds experiment provides a straightforward analogy for the weather phenomena, while the lightning experiment is a more abstract and complex analogy.

A. Clouds in a jar

The steps for this experiment can be seen in Fig. 3. The first step in this experiment is to coat the inside of a large jar with soap; this is irrelevant to the analogy, as it is only to stop the steam from condensing onto the inside of the jar. In step 2, hot water is added to the jar—this is analogous to water on the surface of a planet that evaporates and raises the humidity. In step 3, a bowl of ice water is added to the top of the jar—this simulates a planet’s cold atmosphere and cools the humid air until it is supersaturated. In step 4, a small amount of hairspray is added to the jar—this is analogous to aerosol particles in the atmosphere (dust, smoke, ash) that the moisture in the air will condense onto to form clouds [32]. Figure 4 summarizes the analogy.

B. Lightning sparks

The analogy in the lightning lesson is more abstract. The steps of the experiment can be seen in Fig. 5. In the first step, a thumb tack is pierced through the bottom of an aluminum foil tin, which is pushed into a pencil eraser. This means that the pencil can be used like an electrically insulated handle to pick up the foil tin. This step is irrelevant to the analogy. Step 2 consists of rubbing a piece of wool against a polystyrene tray for 2 min—this is analogous to particles in a cloud being rubbed together by turbulence. Generally, clouds in a planet’s atmosphere will comprise small hard ice crystals and large soft hail particles [33], chapter 1.4.1. The small ice particles lose electrons, and the large hail particles gain electrons. This causes triboelectric charging in the particles being rubbed together. Step 3 is placing the foil tin on top of the charged polystyrene tray. This causes the charges in the foil tin to separate vertically—this is analogous to the vertical charge separation that happens in a cloud when air currents are flowing up. The large (negatively charged) particles move downward due to gravity, and the small (positively charged) particles move up in the atmosphere [33], chapter 1.4.2. Step 4 is to bring a metal fork close to the rim of the foil container and wait for the electrical discharge—this is analogous to cloud-to-cloud lightning occurring, where the

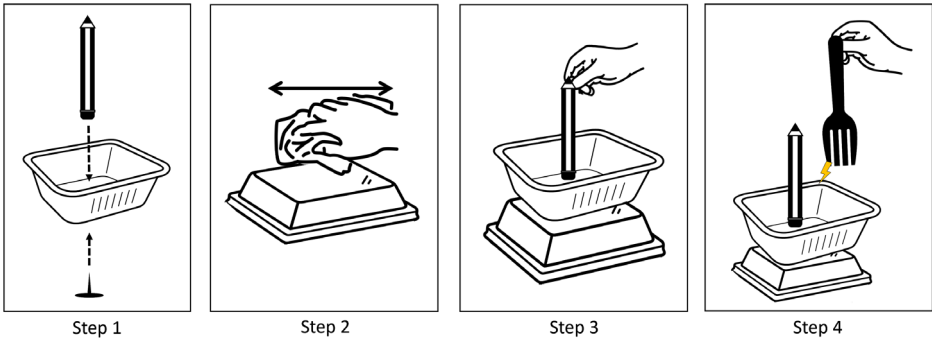


FIG. 5. Each step of the lightning experiment [30]. The items in step 1 are a pencil with an eraser, a thumb tack, and an aluminum foil tray. In step 2, they are a polystyrene tray and a piece of wool. In step 4, a metal fork is introduced.

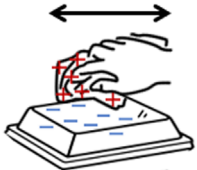
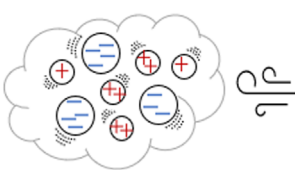
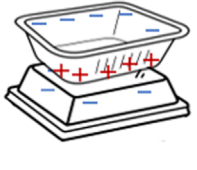
Stage	Experiment	Exoplanet Atmosphere
Triboelectric Charging		
Charge Separation		
Potential Difference		
Electrical Discharge		

FIG. 6. A mapping of each stage of the lightning experiment to each stage of how lightning occurs in a planet's atmosphere [30].

fork acts as another cloud. Figure 6 summarizes the analogy.

IV. METHODS

This study is situated within an interpretative, constructivist research paradigm [34,35], in which learning and reasoning are understood as contextually situated processes. Accordingly, the purpose of the study is to explore and characterize how students use analogies during peer-led discussions following a shared hands-on experience, with a focus on how these analogies are structured and developed in students' joint reasoning. From this perspective, methodological quality is established through theoretical grounding, analytic transparency, and close engagement with empirical data. Our methodological choices therefore include the use of a small number of peer-led discussion groups, qualitative analysis of discourse, and theory-informed, iterative coding, as these are aligned with the goal of producing analytically grounded insights into students' joint analogical reasoning processes. Methodological rigor was supported through a systematically orchestrated data collection design (peer-led

focus groups following the lesson), iterative refinement of analytic categories, and ongoing cross-checking of interpretations among the authors. This approach aligns with prior interpretative studies of classroom discourse that emphasize analytic depth, transparency, and credibility over statistical generalization [36].

A. Lesson and participants

We tested these lessons in Denmark with two classes of science students aged 16 to 18. For practical reasons, the larger class (23 students) participated in the cloud lesson, and the smaller class (5 students) participated in the lightning lesson. These classes were in the same age group but from different schools. The teacher of each class passively attended the lessons. The lessons were 50 min long [29,30], each ending with a brief online question and answer session with an exoplanet scientist from a relevant subfield of research. The lessons and discussions were conducted in English. The two lessons were structured after an inquiry-based model [37], emphasizing students' scaffolded yet autonomous knowledge construction. The data used in this study were collected as audio recordings of peer-led focus groups after the completion of all lesson elements. While the majority of the data come from the cloud lesson, data from the lightning lesson are included to provide instances of different reasoning patterns expected due to the complexity and abstractness of the analogy.

B. Peer-led focus groups

Peer-led focus groups [15], in the context of science education research, consist of a group of students who are given instructions or prompt questions and asked to self-conduct a focus group. This approach was selected as the data collection method for this study for two reasons.

First, the practical benefit of peer-led focus groups is that multiple focus groups can run simultaneously, directly after the lesson, even with limited researchers. This means that the overall time of the data collection is reduced, reducing the time requirements for the school and the teachers. More importantly, it means that students transition directly from the lesson into the discussion session, with minimal time for nonrecorded influences. Second, by using this method, the students' peer discussions are not influenced by the presence of a teacher or researcher.

During the lessons, the students worked on the experiments in groups of two and four. When the lesson was over, they were split into different groups for the peer-led discussion. Lesson working groups were split in half, and each half was paired with a half from a different lesson group, as shown in Fig. 7.

This resulted in eight discussion groups of two to four students (two for the lightning lesson, six for the clouds lesson), each with students from two different working groups. They were split up this way to add variety to the perspectives presented by the students, reduce bias from the

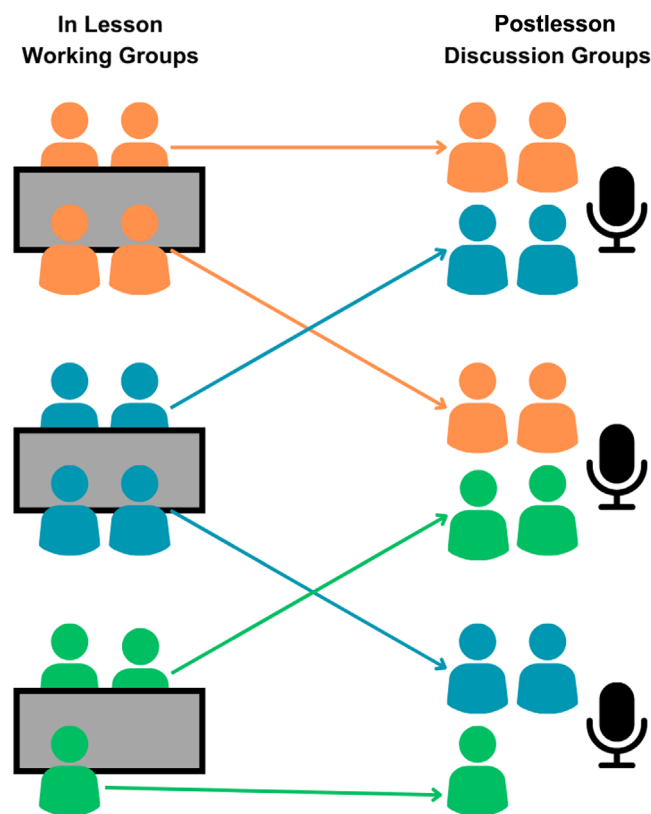


FIG. 7. A visual explaining how the students' working groups were redistributed to create the discussion groups.

way that their experiment went during the lesson, and allow students to articulate their understandings to students they had not previously worked with. Keeping them in working group pairs meant that each student had a person with a shared experience of the experiment as a resource. Discussion groups were put into separate spaces, equipped with a video and audio recorder to capture the discussion.

Each discussion group was given a set of prompts and questions and asked to read through all of the questions, one at a time, and to discuss their answers out loud. They were informed that their answers would not be used for any grading and that it was only to provide feedback to the researchers.

The prompts and questions given to the students were as follows:

- Q1. Explain what you did in your experiment
- Q2. Why was each step of the process necessary to make lightning or clouds?
- Q3. Explain how you can relate what happens in the experiment to:
 - a. What do you see here on Earth?
 - b. What happens on an exoplanet?
 - c. How lightning or cloud formation occurs generally?
- Q4. Thinking back to what you added to the word cloud at the beginning of the lesson, do you feel that

the experiment changed or added to your understanding of how lightning or cloud formation occurs? If yes, then how?

- Q5. How does the experiment you conducted today relate to the research of the exoplanet scientist(s) you spoke to?
- Q6. Are there confusing or irrelevant parts of the experiment? If so, which parts and why?
- Q7. Some exoplanets are tidally locked to their star. This means that the same side of the planet is always facing the star, just like how the moon is tidally locked to the Earth so that we only see one face of the moon. This results in one side of the planet being in constant daytime, and the other side of the planet in constant night. Some scientists predict that tidally locked planets may only have lightning or clouds only on one side, why do you think this might be?

These questions intentionally contain some repetition, allowing students multiple opportunities to discuss and elaborate on the questions. We designed questions 1 through 3 to understand how well the students understood the experiment setup and see if they used the experiment as a physical analogy [16] when asked to compare the experiment to the phenomena in various contexts. These questions provide an opportunity for students to make links between the base domain and target domain [17]. We designed questions 4 and 5 to encourage students to reflect on their learning and provide opportunities to see if the students would use the analogies when discussing the new information that they gained in the lesson. This provided an opportunity for us to see how students used the input spaces and to characterize blend spaces that were created [23]. We designed question 6 to probe students' perceptions of the experiment's analogical limitations. The limitations of an analogy can lead to misunderstandings and misconceptions [6]. The purpose of this question was to investigate how students would discuss these limitations. Question 7 gave students a new problem to solve to apply their learned knowledge, allowing them to potentially use the analogies to aid in answering this difficult question. This question was intended to provide insight into how students could combine the input spaces they have into a new blend [23], which could be used to generate new knowledge.

V. ANALYSIS

Video and audio recorded data were collected from these peer-led focus groups and analyzed. Audio recordings were transcribed while video was used to identify speakers and important gestures.

We transcribed all of the discussions (8 groups, each between 9 and 16 min) and then went through each discussion one at a time to identify moments when students used the experiment as a physical analogy. To select the relevant excerpts, we drew from theory from analogies and conceptual blending [17,23]. The criteria were as follows:

- A student talks about elements or processes from the base domain (the experiment)
- A student talks about elements or processes from the target domain (cloud formation in a planet's atmosphere—Earth or otherwise)
- A student uses terms and processes that are within the blend space (ambiguous terms that could refer to multiple domains or input spaces)

The excerpt size was determined by including all of the information that was relevant to the criteria and enough to provide the context needed, but no more. Rigor was maintained throughout the excerpt selection process by having one author initially select an intentionally large pool of excerpts (including any that the author was unsure whether they met the criteria), which were then cross-checked by a second author to select only those that both authors agreed met at least one of the above-mentioned criteria. The transcription data before and after each excerpt were also assessed by both authors until mutual agreement was reached about the size of each excerpt.

This resulted in 37 selected excerpts (27 from the cloud lesson, 10 from the lightning lesson), which can be seen in Table II in Appendix A. We conducted an initial thematic analysis [38] of these excerpts by hand, sorting them into categories. This process was iterative, beginning with sorting the excerpts into broad categories and then smaller subcategories [38]. These categories were based on the way in which domains [17] and spaces [23] were observed in student discussion; for example, if students mapped a variable from the base domain onto a variable in a target domain, then this would be sorted into the category for variable mapping. We sorted the categories based on what was explicitly said out loud during the discussion, and not on inferred meanings. The categories were cross-checked multiple times between the first and second authors to ensure that the categories were adequate to describe the data, creating new categories where required.

During this process, we frequently referred to the original data set to ensure the context of the excerpts was taken into account and to check for any excerpts we may have missed that fit into the new categories. Once the initial sorting was completed, the categories were given rich, detailed descriptions. The excerpts were then numbered, and two authors separately coded the data. This consisted of them coding each excerpt with as many categories as fit it. This was followed by a cross-coding between the two authors until each category assignment was agreed upon. This process resulted in a list of ways in which the analogies are used in student discussion; these categories are detailed in Sec. VI. There are four broader categories, each with between one and four subcategories.

A. Network analysis

We used network analysis [28,39] as a visual tool to analyze the structure of connections between categories.

For this process, we imported the matrix describing how categories were assigned to each excerpt, shown in Table III in Appendix B, into the network analysis and visualization software GEPHI [40]. This resulted in a bipartite network, which we then collapsed into a co-occurrence network [41]. In this network, links between category nodes are weighted by how many times they co-occur in an excerpt. We removed links from co-occurrences that only happened 1 or 2 times. For this network, this preserved most of the network structure while reducing visual clutter. To show the connections that are most important to each broader category, we created submatrices for the categories. These consisted of only excerpts that had been assigned to the category in question for each submatrix. From these, we created new networks using the same method described above. These new networks show only the co-occurrences that include the category under analysis.

B. Conceptual blend analysis

Our network analyses allowed us to find patterns between input spaces and processes of mapping that students were performing during the peer-led discussions. To understand these patterns in detail, we selected excerpts that illustrate key processes of students using experiments as analogies. We assumed the presence of a blend space in each excerpt and sought to describe this in terms of the “essential aspects of blending” [23], pp. 49–51:

- Input spaces (including a possible generic space) explicitly mentioned, e.g., the experimental input space and Earth as an input space. We also sought to identify base and target domains using the structure *target is like base* from the literature.
- Counterpart connections that were explicitly mentioned, e.g., hairspray from the experiment being a counterpart to dust particles on Earth.
- Selective projections, meaning prominent elements from an input space that was not mentioned in the excerpt, e.g., when discussing the lightning lesson, students may leave out the property of the fork that it is fork-shaped.
- Emergent structures, such as modifications (e.g., introducing and connecting new elements), entrenchments (e.g., prior student knowledge), event integration (e.g., the event of the fork moving close to the metal container *overlaid* by the imagery of clouds moving closer to each other in the lightning experiment), and wide application (for example, if the network of blend space and input spaces can serve multiple goals).
- Elaboration, where we look for evidence that students are treating the blend as a dynamic simulation, for example, imagining where and how the process of cloud formation as conceived in the experiment would happen on a tidally locked planet.

The process of analysis was as follows: The first and second authors selected excerpts and discussed them in terms of the essential aspects of blending described above. They then made a written draft of their analysis and presented it to the remaining authors. The author team then reached a consensus description through discussion.

VI. RESULTS

To address RQ1, we created a broad category called “input space.” To address RQ2, we constructed three additional broad categories that focused on the active use of analogies: (i) mapping between domains, (ii) identifying limitations of the analogy, and (iii) applying the analogy to new contexts. Table I provides an overview of input spaces and analogy use categories 1–3.

Categories 1 through 3 are inspired by previous work on analogical scaffolding [17]; they are made up of uses of the base and target domains and how students can map and use these in their conversations. Input spaces [23] designate relevant subject areas as we observe students referencing them: The experiment (*Input: Experiment*), conditions on Earth (*Input: Earth*), conditions on exoplanets (*Input: Exoplanet*), and physics processes relevant to the lesson (*Input: Physics*). In terms of metaphor theory [16], *Input: Experiment* serves as our base domain during discussions because students are expected to become familiar with that domain during the lesson. The other domains served as target domains.

To address RQ3, we used conceptual blend analysis, as described in Sec. V. Our main finding from this analysis is that categories 1 and 3 could be viewed as evidence of students running a conceptual blend with input from all input spaces. Running these blends appeared to be part of building analogies between input spaces and establishing or fortifying students’ understanding of a given input space. For example, to understand conditions for cloud formation on exoplanets, students had to establish a blend space with inputs from both *Input: Experiment* (base domain) and *Input: Exoplanets* (target domain).

To further investigate the use of these input spaces (RQ1), how they are used in analogical mapping (RQ2) and the resultant blend spaces (RQ3), we used network analysis to investigate the relational nature of these categories. Figure 8 is the result of the network analysis described in Sec. VA. This shows the co-occurrence of all of the subcategories within excerpts. For example, the link of thickness 15 between *Input: Physics* and *Input: Experiment* indicates that these subcategories both occurred in our coding of 15 excerpts.

From this network, we can see that there is copious co-occurrence between categories. The input terms are central to the network, with the strongest edges between them and the other subcategories. The following sections describe the connections from input spaces to the subcategories of each broad category, with examples of the types of excerpts assigned to these categories and a conceptual blend analysis for example excerpts.

TABLE I. Categories and their subcategories that resulted from the thematic analysis of selected excerpts of student discussion.

Broad category	Subcategory	Description	Count
Inputs: Broad topics of discussion	<i>Input: Relevant physics</i>	Students discuss and/or explain physics terms and processes	18
	<i>Input: Earth</i>	Students reference conditions on Earth or from their everyday experience	12
	<i>Input: Exoplanets</i>	Students reference conditions on planets other than Earth	13
	<i>Input: Experiment</i>	Students mention the experiment that they conducted in class	28
1. Mapping between source and target domains	<i>1a. Mapping variables</i>	Students state that they are comparing one variable in one of the domains to another variable in another domain	10
	<i>1b. Mapping processes</i>	Students map one of the processes happening in the analogy between the domains	6
	<i>1c. Mapping to exoplanet contexts</i>	Students map from either the experiment or real life to an exoplanet (or general planet) context	12
	<i>1d. Ambiguous terms</i>	Students use a term, variable, or expression that could be applied to either the base domain or target domain conceptual metaphor terms	14
2. Identifying analogy limitations	<i>2a. Nonmappable variables</i>	Students mention an element or variable of the experiment that does not have an analogical parallel	9
	<i>2b. Redundant experiment elements</i>	Students mention a part of the experiment that is redundant	3
3. Applying the analogy to new contexts	<i>3a. Extending the analogy</i>	Students apply the analogy to a context outside of their everyday reality and the experiment	5

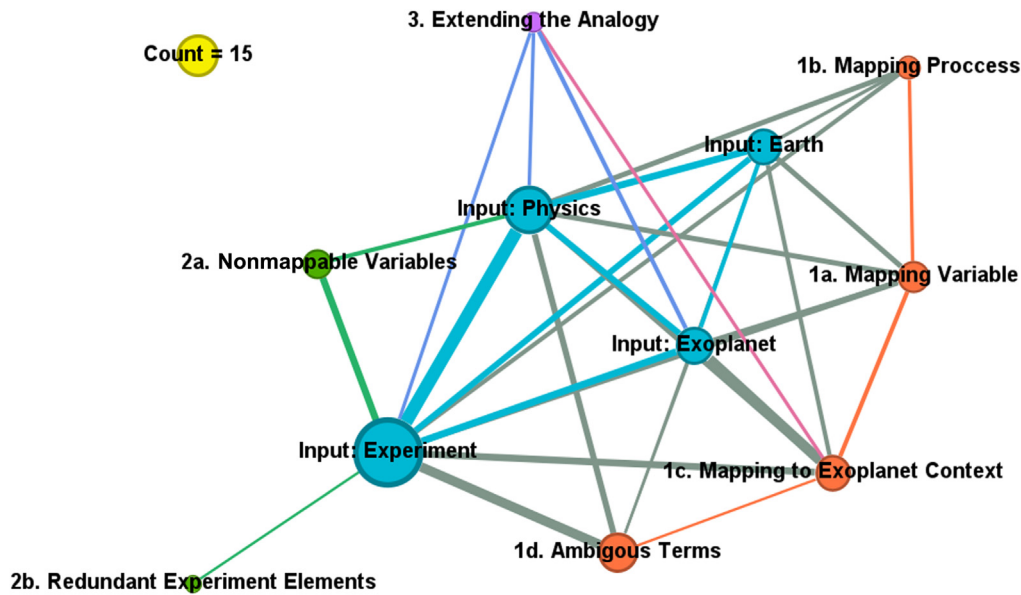


FIG. 8. Category co-occurrence network for all subcategories. Nodes represent subcategories (see Table I). Weighted links represent the number of co-occurrences in excerpts. Node sizes are proportional to the number of excerpts that were assigned to the corresponding subcategories.

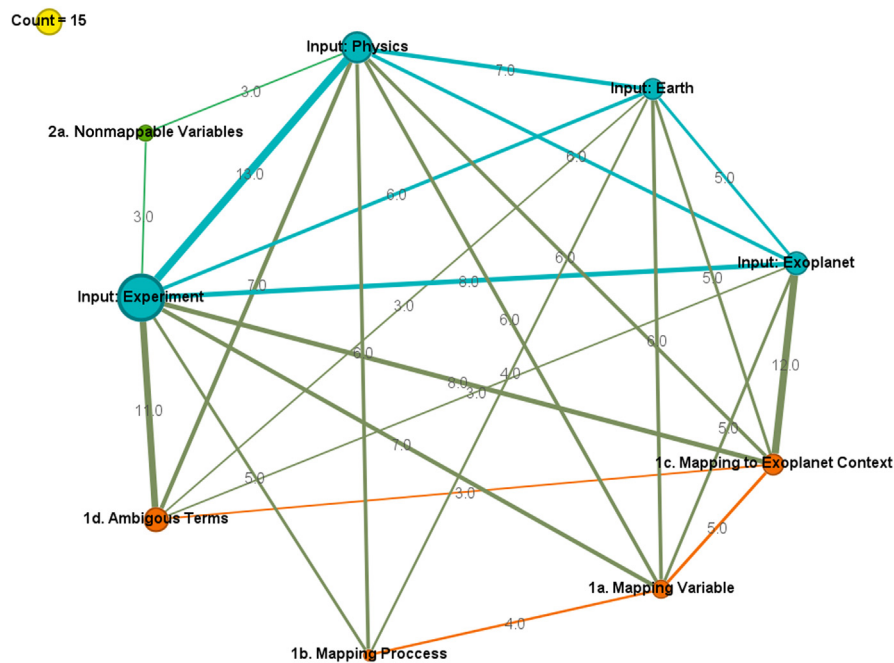


FIG. 9. Category co-occurrence network for excerpts that were assigned to broad category: *1. Mapping between source and target domains*. Nodes represent subcategories (see Table I). Weighted links represent the number of co-occurrences in excerpts. Node sizes are proportional to the number of excerpts assigned to the corresponding categories.

A. Mapping elements of the analogy

Figure 9 was created from the excerpts that had been assigned to category *1: Mapping between source and target domains*.

The network shows that the strongest connections from each of the subcategories are to input spaces.

1. 1a. Mapping variables

Students were seen to map specific variables between the base domain (*Input: Experiment*) and target domains (*Input: Earth*, *Input: Exoplanet*, and *Input: Physics*), as seen in the following excerpt from the cloud lesson discussion:

- S1: I mean, all the different parts could be related to different elements of the Earth. For example, the cold water at the top of the jar would be the outer atmosphere, where it's obviously colder.
- S2: Yeah, the hot water at the bottom could be the heat radiated from the Earth. Yeah, so it's warmer on the ground. Yeah, the surface temperature.
- S3: also the aerosol could be like dust.
- S2: Yeah! So instead of the Earth being covered in hairspray, it would be dust particles to stick to, which is... yeah.. why we get the clouds we have here. (excerpt 20, cloud lesson)

In this example, the students map variables in *Input: Experiment* to their analogical equivalent variables in *Input: Earth* (e.g., cold water $\leftrightarrow$ outer atmosphere and hot water $\leftrightarrow$ warm ground, aerosol $\leftrightarrow$ dust). We also see evidence of the more generic *Input: Physics* space in their referencing to heat radiated from Earth and to surface temperature.

In this example, we could not see clear evidence that the mapping always goes from our intended base domain, the experiment, to a less-known target domain, Earth, physics, or exoplanet. For the first two statements, the experiment is linguistically the target domain (using the *target is base* structure). For S3, the domain to which aerosol belongs is then the target and dust (probably known from Earth) belongs to the base. Following the *target is base* structure, we could conclude that the students are using Earth and physics to understand the experiment. However, the final statement concludes on cloud formation on Earth, so students may also learn about what we took to be the base domain. Therefore, we argue that instead of having target and base domains, input spaces seem to act as scaffolds for each other. We saw the same pattern in the rest of the excerpts.

In terms of blend spaces, mapping of variables can be seen to take place within a shared blend space that supports students' developing model for cloud formation. This blend space contains a selective projection [23], p. 47, where students retain key functional elements from input spaces (particularly the elements that are mapped), while leaving out others, such as the jar. An emergent structure [23], pp. 48–49 appears toward the end of the excerpt, where student 2 modifies the blend by invoking the image of the Earth being covered in hairspray, which is then mapped to dust. Thus, in the blend space, the hairspray can easily be seen to cover the Earth and then be transformed into dust particles. The blend space seems to provide an arena that allows students to make analogical mappings. Students were also seen to identify variables that are the same in both the *Input: Experiment* space and the *Input: Earth* space, such as the water in the cloud experiment:

Yeah, on Earth it is basically just.. we have water as the water vapor. (excerpt 9, cloud lesson)

This is an example of a more direct mapping between input spaces, illustrating that counterparts in each input space can be identical. It can be seen in Fig. 9 that the category for *1a. Mapping variables* co-occurs with each of the input spaces at least 5 times. This indicates that students create blend spaces and use them dynamically to map between input spaces in developing their understanding of cloud and lightning formation.

2. 1b. Mapping processes

Students were seen to not only map the variables between *Input: Experiment* and other inputs, but also map the processes occurring within these. An example of this is seen in the excerpt below:

- S1: When there are two clouds, one is very positive and one is very negative.
- S2: no...It was more like...
- S3: They split up, like the metal container. So like the bottom got negative and the top got positive because of like big and small things inside the cloud
- S1: When another cloud also comes, it makes the opposite of what is closest to it.
- S3: yeah, the cloud coming is like the fork...
- S1: So there will be a positive and a negative end of the clouds and then it makes lightning. (excerpt 32, lightning lesson)

This example shows how students explicitly run the blend between *Input: Experiment*, *Input: Physics*, and *Input: Earth*. Like the example above, we see mapping of variables (e.g., metal container, fork $\leftrightarrow$ cloud) and selective mapping (the facts that the fork and metal container are both made of metal are not mapped). However, the blend also allows for the imaginary process of moving clouds by referring to the process of moving the fork toward the metal container. This allows the students to use the discussion to run a blend that is a model of lightning formation. In our interpretation, the blend space allows students to use their experiences from the experiment to construct knowledge about cloud formation on Earth. Figure 9 shows that the node for *1b. Mapping processes* has the most co-occurrence with students discussing the experiment and physics. This is likely because the majority of the processes being described are physical processes within the experiment that have a counterparts in physics.

3. 1c. Mapping to exoplanet contexts

In addition to mapping the experiment to variables and processes on Earth, students were also observed to map the variables onto exoplanet conditions that were introduced to them during the lessons. An example of this can be seen in the excerpt below:

- S1: [Reading the question]: Explain how you can relate what happens in the experiment to what you see here on Earth.
- S1: [Talking to peers]: Well, maybe like there's [...] maybe there are small impurities in the air that sort of work as these aerosol particles, where like when the water... When the water vapor... Well, when the water evaporates, it will rise. Because we know hot things tend to rise, or cold things tend to... Whatever. And this water vapor will then perhaps condense onto small impurities or just particles in the air. We talk about dust and pollen as being things that can condense onto. So that's what we see on Earth. And yeah, what we see on Earth is water that is condensing. But what happens on exoplanets is that could be any sort of chemical or just liquid that can evaporate, can form a cloud, from at least what I've understood so far. (excerpt 16, cloud lesson)

In this excerpt, direct reference is made to *Input: Earth* and *Input: Exoplanet*. The student also makes use of *Input: Physics*, for example, "hot things tend to rise." We expect that "hot things tend to rise" is prior knowledge that the student can easily draw on when running the blend; thus illustrating that students also make use of *entrenchment* [23], p. 52. *Input: Experiment* is the departure point, and in talking to peers, we see the student as doing a process of elaboration, where they talk through a simulation of how cloud formation happens on Earth. This elaboration likely builds on both the generic *Input: Physics* space and the *Input: Exoplanet* space. Interestingly, the *Input: Exoplanet* is activated only near the end, where it modifies the blend that is being run and widens its application to "any sort of chemical or just liquid that can evaporate." This illustrates how students may extend the analogy out from experiences made during the experiment to the broader context of exoplanets. The network in Fig. 9 supports this in that *1c. Mapping to exoplanet contexts* co-occurs with all four inputs, but strongest connections to the experiment, and to exoplanets.

4. 1d. Ambiguous terms

The mapping of variables and processes is sometimes explicit, as seen in the excerpts above. Students may also engage in mapping by using ambiguous terms that could apply to multiple input spaces or domains.

This can be seen in the following excerpt from the lightning lesson discussion:

- S1: We rub the plastic one with wool for two minutes and put the metal on it.
- S2: Yes, the metal container on the plastic container and then...
- S1: I've put a fork close to the metal container to....

- S2: ...make thunder, a thunder sound.
- S3: And lightning (excerpt 30, lightning lesson)

This excerpt is interesting because it only explicitly contains *Input: Experiment*, but seems to connect cause and effect in both *Input: Experiment* and *Input: Earth*. Initially, students 1 and 2 are only discussing the variables in the experiment until student 2 brings up thunder (a variable from *Input: Earth*) and then corrects themselves to say "a thunder sound," relating it back to the experiment and making the distinction clear. Student 3 then includes "lightning" in the discussion, which is a variable from *Input: Earth*, making no clarifying connection or relation to the experiment. The terms are used ambiguously, and it is difficult to make a clear demarcation of either input spaces or their mappings. The discussion can be seen as a simulation of the experiment that links cause (two charged bodies moving toward each other) in *Input: Experiment* with effect (thunder and lightning) in *Input: Experiment* and *Input: Earth*. Thus, in running the blend, students seem to solidify an understanding of cause and effect for thunder and lightning.

B. Identifying analogy limitations

Figure 10 was created from only the excerpts that had been assigned to category: 2. *Identifying limitations of the analogy*.

1. 2a. Nonmappable variables

In question 6 (see Sec. IV), the students were asked if there were any confusing or irrelevant parts of the experiments. In the clouds lesson, students identified that the soap was used as an antifogging agent for the experiment and did not have a comparison in the real-life world. Students also identified that the jar was a size limit for the experiment which did not exist in real life. These can both be seen in the excerpt below:

- S1: I don't think we did anything that wasn't necessary. Of course, like, the soap that was in the jar wouldn't actually be present in an atmosphere or like in...
- S2: But the soap... was just to like make it like the water doesn't like attach
- S1: But what I'm saying is that wouldn't actually happen in the atmosphere, so that would be unnecessary out there. It's just to represent how it works. Like in the atmosphere we don't have a jar. It's just air around.
- S2: yeah, of course, I mean the whole atmosphere is like the jar you know?
- S1: Yeah, kind of. But like, the soap isn't necessary here...
- S2: We needed to soap just to see what was going on in the jar. (excerpt 17, cloud lesson)

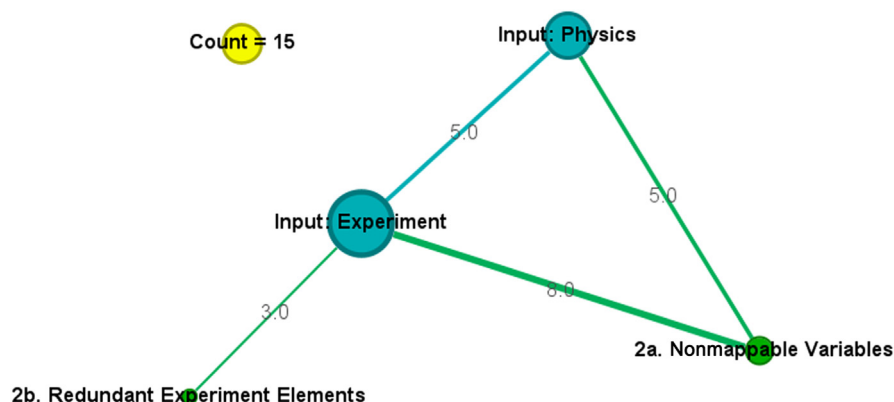


FIG. 10. Category co-occurrence network for excerpts that were assigned to broad category: 2. *Identifying limitations to the analogy*. Nodes represent subcategories (see Table I). Weighted links represent the number of co-occurrences in excerpts. Node sizes are proportional to the number of excerpts that were assigned the corresponding categories.

The role of this part of the discussion in terms of the conceptual blend differs from what we have seen previously. We don't see students mapping between input spaces or running a simulation in a blend. Instead, the episode can be seen as the act of consciously doing selective projection. This means that students were prompted to, and did, reflect on what parts of the experiment should *not* be included in their analogy. In Fig. 10, it is clear that the most common co-occurrences with mentioning nonmappable elements of the experiment are using the input spaces of Experiment and Physics.

2. 2b. Redundant experiment elements

Students in the lightning lesson identified the pencil being used as a handle as a limitation of the analogy. The purpose of the pencil in the experiment was to act as an insulating handle so that the metal tray could be manipulated without affecting the charge in it. However, the students in this lesson were given access to rubber gloves, therefore making the pencil precaution redundant. Students reflect on this in the following excerpt:

- S1: I understand everything, but I would also say I didn't really know what the pencil was for.
 S2: The pencil also wasn't quite needed and the reason for that is because we had the rubber gloves also. Because the only reason for the pencil was that way we could move it onto the polystyrene without touching it and so we wouldn't discharge it instantly.
 S1: Yeah, so if we had...
 S2: But because we have the gloves on, that didn't really... Yeah, that didn't matter. (excerpt 28, lightning lesson)

This example also shows an act of conscious selective projection prompted by the questions. On top of not having

a counterpart in the target spaces, the pencil was also identified as redundant.

Figure 10 shows that *2b. Redundant experiment elements* only co-occurred with *Input: Experiment*.

C. Applying the analogy to new contexts

In addition to using the analogy for clarification and explanation, we saw that students also extended the analogy during problem solving.

1. 3a. Extending the analogy

Question 7 (see Sec. IV B) asks the students about tidally locked planets, and where they would predict clouds or lightning to form on these planets. The following excerpt is from the cloud lessons:

- S1: The side of the planet that's facing the star at all times is very, very hot at the surface because of the planet, and also very hot at the top of the atmosphere.
 S2: It would be like doing this experiment without the cold water.
 S1: So that wouldn't have clouds. But on the cold side where it's constantly dark, there's no sun to heat up the outer atmosphere. So that's the cold water. (excerpt 23, cloud lesson)

Student 1 describes the problem statement in reference to the reality of tidally locked planets. Student 2 finds an appropriate analogy for a hypothetical experiment setup that would match these conditions. Student 1 then draws a conclusion of this hypothetical experiment and uses this to make a hypothesis for how clouds would form on tidally locked planets. The students make direct reference to elements in both *Input: Experiment* (doing the experiment without cold water) and *Input: Physics* (heating up the outer atmosphere, for example). In this blend, the key

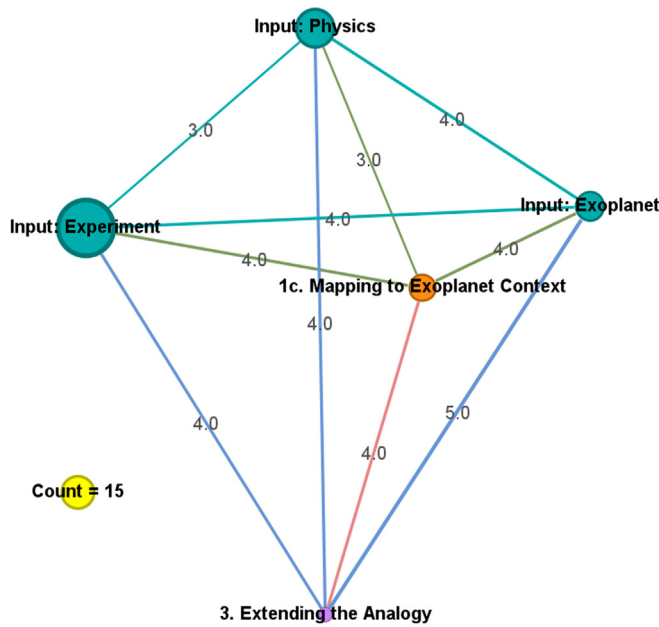


FIG. 11. Category co-occurrence network for excerpts that were assigned to broad category: 3. *Applying the analogy to new contexts*. Nodes represent subcategories (see Table I). Weighted links represent the number of co-occurrences in excerpts. Node sizes are proportional to the number of excerpts that were assigned to the corresponding categories.

mappings between input spaces are: experiment without water $\leftrightarrow$ dayside of the tidally locked planet, and the cold lid on the jar $\leftrightarrow$ nightside of the tidally locked planet. We argue that the conceptual blend being used here is a secondary blend that students can use to make predictions about tidally locked planets; this is shown in more detail and context in Sec. VII.

Figure 11 shows that the node representing 3a. *Extending the analogy* is linked with three input spaces: *Physics*, *Experiment*, and *Exoplanets*. This node is linked just as strongly to the node representing 1c. *Mapping to exoplanet contexts*.

VII. DISCUSSION

We set out to answer the question: How can upper secondary school students use experiments as analogies during peer-led discussions that take place after the lesson? Our discussion focuses on using our results to answer this question based on our subquestions (see Sec. II C).

A. RQ1: Use of input spaces as base and target domains

The input spaces identified in the student discussions are: relevant physics (*Input: Physics*), Earth conditions (*Input: Earth*), Exoplanet condition (*Input: Exoplanet*), and the in-class experiment (*Input: Experiment*). Figure 8 shows that the input spaces are central to the category co-occurrence network, and Fig. 9 shows that all of the nodes in the mapping category are primarily connected to input spaces.

We originally viewed lesson analogies as bases for structure mapping [42]. The base domain was intended to be the hands-on experiments, and the target domain was intended to be either cloud formation or lightning occurrence in both Earth’s atmosphere and exoplanet atmospheres. We expected relations to be mapped from the base to one of the targets and we did see instances of students mapping processes and variables between the *Experiment* input and the inputs of *Earth* and *Exoplanets*. However, as seen in Fig. 9, subcategories relating to the mapping between domains were commonly occurring with *all* of the identified input spaces. Furthermore, we could not see clear evidence of mapping from a single base domain to a target domain (see Sec. VI A 1). This suggests that in using experiments as analogies, all of these inputs can be used flexibly as base and target domains.

Table I shows that *Input: Experiment* is used most often, likely due to the prompt questions and to students having just finished a lesson with the experiment. However, in our categorization of excerpts, each of the inputs can be found in combination with nonexperiment inputs (see Appendix B). For example, some excerpts were only assigned *Input: Earth* and *Input: Exoplanets*, and some were assigned *Input: Physics* and *Input: Exoplanets*. This shows that although the experiment input is most commonly used, it is not used in every mapping. This suggests that there are times when students will be using one of the other inputs as the base domain and may form new unexpected analogies. This aligns with the suggestions of Spiro *et al.* [43] to teach using multiple analogies. Podolefsky and Finkelstein [17] state that “no single analogy is sufficient” in teaching, and propose using “multiple, layered analogies” that are dynamic and flexible to the students’ thinking. This line of thinking takes us to our next research question, addressing the analogical mapping that occurs during student discussions.

B. RQ2: Analogical mapping processes

The resultant categories from the coding revealed multiple ways in which students create and use analogies by mapping between domains. We can see from the results (Sec. VI) that students mapped between variables, processes, and contexts. The usage of categories 1a. *Mapping variable* and 1b. *Mapping processes* showed that students did indeed map between domains. Using Gentner’s definition of structure mapping for analogies [42], the *relations* between objects need to be mapped between input spaces (base and target), and not the objects’ attributes. This could suggest that the mapping of variables alone would not constitute a structure mapping. However, students do not generally treat the variables and experimental objects in isolation and do not only address superficial attributes. Instead, they discuss object relations in the experimental spaces, like fork-to-metal-container in the lightning experiments, to their counterparts in the Earth and exoplanet

spaces. They tend to discuss variables as something to be varied that will have an impact on the rest of the experiment. We argue that in this context, both the mapping of processes and variables is a type of relational mapping, as both are being discussed in relation to their overall context.

As discussed in Sec. VII A, we argue that students sometimes used multiple input spaces to produce blend spaces as part of their analogical reasoning. This is illustrated most clearly in Fig. 8, where *1c. Mapping to exoplanet contexts* is connected to all four input spaces. However, this does not mean that students needed to invoke all these input spaces each time they made an analogy. In some cases, they did invoke all four, but in other cases, they invoked two or three. This created many different but related analogies.

Spiro *et al.* [43] suggest teaching using multiple analogies as more complete than using only one. In addition to this, Gentner [44] showed that explicitly teaching students analogies was not as effective as if they created the analogies themselves. Therefore, we argue that allowing students to use peer-led discussions to create their own blend spaces, to create multiple, layered analogies, could be a powerful way of letting them explore their work with an experiment to learn through analogy. That is, by prompting them to reflect on how the experiment relates to the phenomenon they are to learn about, we see postlesson reflections as a potentially useful way for students to process and learn from their engagement with the experiment in the lesson.

The last subcategory for the category *Mapping between source and target domain* is *1d. Ambiguous terms*, where students use terms that could belong to numerous domains. Podolefsky and Finkelstein [17] draw on conceptual blending in their model of analogical scaffolding when considering multiple analogies to be used by students. We argue that the multiple analogies in this study exist in conceptual blend spaces. We have described specific blend space applications for each excerpt in Sec. VI, and will now discuss a hypothesized overarching blend space in which these ambiguous terms can be applied.

We have exemplified how the multiple analogies used by students in their postlesson discussion operate within a conceptual blend space between input domains. We propose an overarching structure in line with Fauconnier and Turner's [23] basic structure for conceptual blend (Fig. 1), where *Input: Physics*, the physics content that is relevant for the lesson, acts as the generic space, while the experiment and Earth conditions act as inputs. Mapping via analogy then takes place within a blend space that students construct, in our study via their peer-led discussions. Figure 12 illustrates a possible version of a corresponding blend diagram for the cloud lesson.

One interesting proposition of conceptual blending is that we as humans have the ability to “run” a blend and produce new information [23]; this can be used to gain a

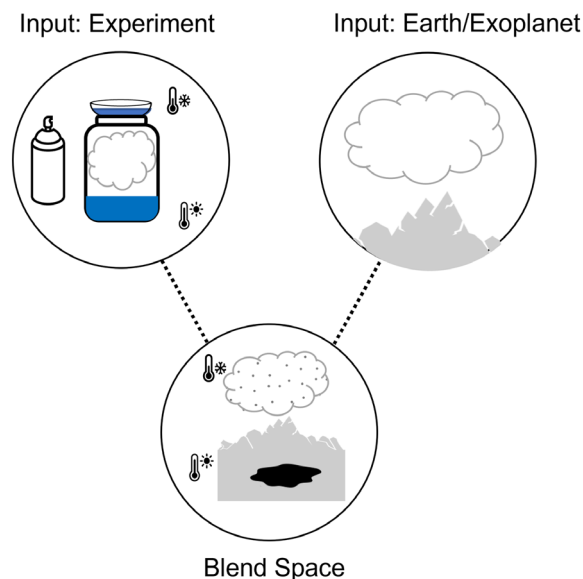


FIG. 12. A diagram showing a conceptual blend [23] between the experiment and conditions on Earth and an exoplanet resulting in a combination of elements of both.

new understanding of a topic. For example, students in the example for *1b. Mapping processes* (Sec. VI A 2) ran the blend where fork and metal container map to two clouds and express the understanding that the clouds must have a positive and a negative end. We see this as an example of running an analogy in the blend space.

As discussed in Sec. VI C, students who were extending the analogy used *Input: Experiment, Physics, and Exoplanets* and were often mapping to (a new) exoplanet context. They did not seem to map directly from these three input spaces to the new exoplanet context, but needed to have already blended the experiment, relevant physics, and exoplanet input spaces. This implies that students likely used their previously established blend space as a new input space from which they then created a new blend.

As an illustration, consider *Tidally locked planets* as a new input space. This is relevant, when students discussed the concept of tidally locked planets, as prompted by question 6 (see Sec. IV B). The concept of tidally locked planets was new to students, so the input space for tidally locked planets will depend on the information given to students in the problem. We propose that the new tidally locked planet input space was blended with the previous resultant blend from Fig. 12. Figure 13 visualizes this second blend.

In their discussions, we saw students apply their knowledge of the experiment and its resultant meaning for the new conditions that were presented in the form of the tidally locked planet. This resulted in a new blend space in which a simulation was run to imagine an experiment under the new conditions (see quote in Sec. VI C: “It would be like doing the experiment without the cold water.” In the language of conceptual blend theory, this allowed the

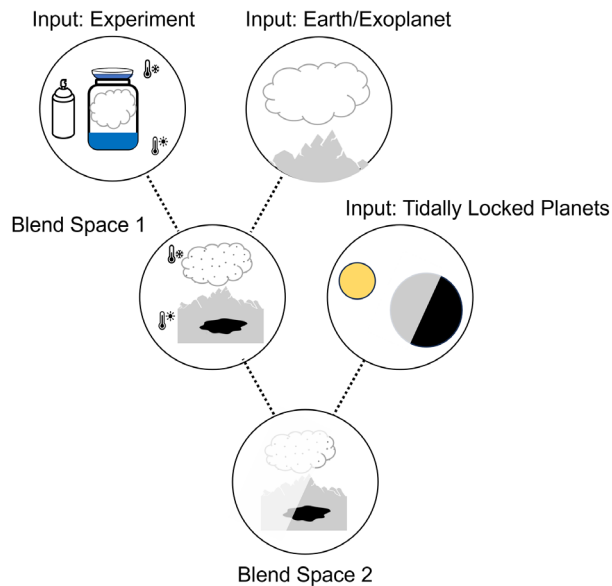


FIG. 13. An extension of the conceptual blend seen in Fig. 12, where the previous resultant blend is now an input space for a new blend.

students to tentatively integrate cause and effect and predict that the day side of a tidally locked planet will not have clouds.

C. Contributions to conceptual blending theory in physics education research

This study contributes to physics education research by extending the empirical application of conceptual blending theory and by developing an empirically and analytically grounded account of how blend spaces function in collective reasoning contexts.

In terms of empirical scope, the present study extends prior applications of conceptual blending theory in physics education research. Previous studies have examined the dynamics of blending either during interaction with representations or artifacts, or through analyses of individual reasoning. Gire and Price [24] demonstrates how conceptual blends are constructed as students coordinate conceptual and representational features of electric field vector arrows, highlighting the role of representational materiality in individual reasoning. Similarly, Gregorcic and Haglund [45] analyze how blends emerge and develop through embodied and collaborative interaction with technological representations during an activity. While these studies provide important insights into the temporal development of blends, they focus on blending processes that occur while students are directly engaged with representations or artifacts.

The present study instead examines how conceptual blends are constructed and negotiated after a shared hands-on experiment, in peer-led discussions where the physical phenomena are no longer directly accessible. This

shows that hands-on experiments can function as persistent input spaces in blending processes beyond the activity itself, as elements of the experimental experience are selectively recalled, and reinterpreted through discussion. In this way, the study highlights how remembered experience can play an active role in analogical reasoning, even in the absence of the physical setup. Although the peer-led discussions analyzed here were organized as a research setting, they mirror important features of small-group work in physics classrooms, including student-initiated talk and collective negotiation of meaning.

Beyond this extension of empirical focus, the study also contributes to how conceptual blends are theoretically characterized in physics education research. The blends identified in this study are not stabilized by immediate perceptual access to material or representational resources as they are in other studies [24,45]. Instead, blends in our study are constituted through selective and collective reconstruction of prior experience. As a result the blend spaces observed in the peer-led discussions are often partial, ambiguous, and internally heterogeneous.

Importantly, this ambiguity appears to be productive. The underspecification of blend spaces allows different students to project slightly different meanings while still coordinating their reasoning, enabling blends to function as flexible reference points in interaction rather than as fully elaborated or stable conceptual structures. This aspect of blending is not foregrounded in previous conceptual blend-focused studies in physics education. These tend to emphasize how blends are constrained and stabilized by representations or artifacts present during the activity. The present study therefore highlights that openness and negotiability can help construct blends through discourse.

Related work in science education has highlighted the importance of student-generated analogies in learning. In particular, research on self-generated and collaborative analogies has shown that students often construct analogical connections that are not fully specified in advance and that evolve through interaction (Haglund [46]). While Haglund's [46] body of work is not explicitly framed in terms of conceptual blending theory, it similarly emphasizes the open-ended, negotiable, and socially situated character of students' analogical reasoning. The present study aligns with this research but adds to it by providing a conceptual-blending-based analysis of how student-generated analogies are constituted as blend spaces in peer-led postexperimental discussions. Thus, this work offers a conceptual-blending-based account of the mechanisms by which these flexible analogical constructions support collective reasoning.

Taken together, these findings extend existing applications of conceptual blending theory in physics education by showing that blends can be collectively constructed after hands-on experimentation. Such blends are grounded in remembered material experience rather than immediate

interaction with artifacts, and characterized by a degree of productive ambiguity. Rather than treating conceptual blends primarily as coherent cognitive constructions or intended instructional tools, the present study foregrounds their role as dynamic, interactionally sustained structures that support joint reasoning in classroom-relevant contexts.

D. Reflections on the use of peer-led focus groups as a method

We found that our use of peer-led focus groups in this study provided access to unfiltered, spontaneously generated analogies. This setting allowed all of the students to enter the discussions directly after the lessons. This meant that students did not have much time after the lesson to discuss among themselves without a recording apparatus and thus get answers to all of their initial questions and settle any confusion.

These discussions were held in the absence of a teacher or authority figure. This gave the students the opportunity to discuss their understandings without deferring to a teacher or asking for input. Being put in this position gave students the opportunity to rely on shared blended space for analogies.

In our view, these benefits outweigh some of the limitations of the method. While students did to some extent discuss things that were off-topic, they were not fundamentally hindered in their engagement with the topic. Another possible limitation would be that there is no researcher to guide students if they veer off in a different direction than intended. We tried to safeguard against this with relevant questions and by notifying groups about how much time they had left.

A clear limitation of the method is that we, as researchers, do not have the possibility of asking clarifying questions. For example, if given the opportunity, we would have asked the students to try to go back and finish a sentence if they are interrupted or if they drift off-topic. We could also have asked students whether they had a specific domain in mind when they mentioned ambiguous variables. The extent to which we can get clarification of student thinking hinges on whether other students ask them to elaborate. Whether it is possible to get students to ask for clarification from other students could be investigated in the future.

Although postlesson student discussion or summarizing could be an in-class part of a lesson plan, this was not the case in this study. We explicitly told the students that the class had ended and that they would be participating in data collection for a research project. By doing this, we reframed an activity that students are familiar with (peer discussion) into a new context, with a new motivation: being part of a research project. By making it clear to the students that this was the motivation for their discussion, the intention was to encourage them to provide elaborate and detailed responses for research purposes, not just for themselves or to perform

for a teacher. While we cannot claim that student discussions were the same as what they would do in everyday teaching, this method of orchestrating feedback provided usable data for our analysis.

E. Limitations to the study

Apart from the limitations of the method, this study has other limitations as well. It was a small study conducted with only two classes in one country (Denmark) and at one level (upper secondary). In future research, it would be of interest to repeat a similar study with a larger and more diverse sample. In addition to this, the class sizes were uneven, resulting in one lesson topic being discussed more than the other. Additionally, we are aware that the conceptual blends that we have described in this study are based on our inferences from the data and that there are many possible ways in which this data could be interpreted through different lenses or experiences. We arrived at categories and coding of the data through consensus. For a larger dataset, categories and coding could be further validated through, for example, more rigorous tests of interrater reliability and coupling to measures of student learning.

We also see a theoretical limitation to our study. While we refer to many student utterances as analogies, we acknowledge that some may be better described as *identifications*—where elements are treated as the same across domains [23]. We have also not systematically distinguished between *near* and *far* analogies, although this difference can shape how readily students make connections [47]. Our focus has been on students' dynamic use of input spaces, whether through analogy, identification, or blending. Future work may benefit from explicitly disentangling these categories, especially in relation to conceptual development.

F. Implications for teaching

Despite these limitations, the findings of this study point to features of postlesson peer discussion that may be analytically informative and worthy of further exploration in other contexts. In this study, students were observed to reflect on their practical work and to relate it both to everyday experience and to newly introduced domains, such as exoplanets. Previous research has noted that the role of practical work in science teaching is often ambiguous and undertheorized [48]. The present findings suggest that opportunities for peer discussion following practical work can provide a context in which students articulate and negotiate analogical connections across domains.

In particular, peer discussion following hands-on experimentation appears to afford opportunities for students to generate and explore metaphorical projections and self-constructed analogies, consistent with prior work on analogical reasoning and learning [44,46]. Such contexts may therefore be of interest when considering student-

centered teaching formats that emphasize learners' active role in consolidating and extending their understanding [49].

VIII. CONCLUSION

In this study, we found that students used hands-on experiments as a physical analogy in multiple ways. By analyzing audio recordings of student peer-led discussions taking place immediately after a hands-on lesson on either lightning or cloud formation, we found that students were able to identify variables between the domains of the experiments and the domains of physics, Earth contexts, and exoplanet contexts. They were able to identify which variables, components, and processes of the experiment did and did not have counterparts in other domains. Rather than mapping from a well-known base domain to a less-known target domain, we found that students ran conceptual blends with input from all domains. We observed students using this blend space to build their understanding of elements and processes in all relevant domains (the experiment, physics, Earth, and exoplanets). We also saw students constructing a secondary blend space, consisting of blend spaces they had previously established and the domains of the experiment, physics, Earth, and exoplanet contexts. This secondary blend space allowed them to hypothesize about tidally locked planets (a novel topic to them) through the use of the physical analogy of the experiment. Our findings show that peer-led discussions immediately following hands-on experimentation can serve as sites where

students jointly construct and negotiate shared understandings of astronomy concepts.

IX. DECLARATIONS

A. Ethics approval

Ethical clearance for this project was granted by both the independent Ethics Committee for the Social Sciences and Humanities (EASHW), installed by the Executive Board of the University of Antwerp and the Faculty Secretariat at the Department of Science Education at Copenhagen University.

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The authors report there are no competing interests to declare.

DATA AVAILABILITY

The data supporting this study's findings are available within the article.

APPENDIX A: EXCERPTS

TABLE II. Selected excerpts from student discussion, as described in Sec. IV.

No.	Excerpt
1 (Clouds)	We put variables in an environment of a closed chamber of the formation of clouds.
2 (Clouds)	The soap was necessary [...] to prevent the water, because when the water was like this [hands moving up and down and side to side], it would have just stuck to the glass and not to the aerosol because it would much rather go to the glass than the aerosol.
3 (Clouds)	S3: "You can see that we have a very cold atmosphere, when you get up there [gestures to the sky] so and it's so it's the same. The same process kind of that you have the cold and hot [gestures hands up and down]." S4: "And that air, cold air, or cold 'water' up here [points to the sky] and warm water, or warmer water down here [points to the ground]. And then we see the same fluctuation [alternates hands up and down] and we see this over humidify, or this over saturation." S2: "Yeah, the surface heat making it rise."
4 (Clouds)	S4: "Then we see the dust that gets kicked up, and dust and sand and dirt." S2: "Yeah, the dust is..." S4: "The aerosol." S2: "Yeah, the aerosol."

(Table continued)

TABLE II. (Continued)

No.	Excerpt
5 (Clouds)	This is not an exoplanet, but on Jupiter, there could be aluminum clouds because the aerosol could be the gases and the... which is a liquid form so we can use metals and such so very unique forms of clouds depending on the environment on the planet.
6 (Clouds)	So essentially we tried to imitate an atmosphere by having a warmer surface and then a colder top. So the top of the air in the jar was colder because we had cold water on top. And then by spraying aerosol in we added some particles, some solid particles that the water could condense around.
7 (Clouds)	if we relate to the atmosphere, the hot water comes from the fact that the Earth is warmer, I guess. Yeah, and it comes from the fact that the atmosphere is warmer.
8 (Clouds)	S1: not the Earth but like a.. planet S2: oh yeah S2: Yeah, the planet, the planet has heat right so water is emitted also when also when there's sunlight on it and it's evaporating the water or the liquids. Step two I guess it's because the atmosphere doesn't get heated as much by the planet itself as the surface, the aerosol is just general materials in the atmosphere so depending on what materials or elements are on the planet that's going to be different aerosols but there's always going to be some aerosols if there's clouds right and the last step is just yeah it's just all these yeah all these condensated water particles in the air that are proximate to each other
9 (Clouds)	S1: Yeah, the Earth is basically just, we have water as the water vapor, we have dust and pollen and stuff as the aerosols. S2: Dust, pollen, smoke as the aerosol. S1: Yeah and then we have a warm Earth and then a colder atmosphere. On exoplanets, I mean the one we did first was general right? The one we explained before was general. So on exoplanets it could be different materials that form the aerosols, it could be different vapors.
10 (Clouds)	S4: Well, I guess the soap isn't really necessary. S1: No, no, the soap is necessary, otherwise the glass fogs. S4: Yeah, I know, but it's necessary for the cloud to...
11 (Clouds)	S1: It's just to make observation easier. It could be confusing, I guess, if you weren't explaining that part. [Answering Tidally locked planet question] S1: Because—I'd say the side that faces away from the sun—yeah, it's too cold. So there's not going to be any moisture in the air because it's going to have frozen, right? S4: Yeah, so that would like the variable of the heat component. Yeah, we also did in the experiment S1: We would be removing the aspect of.... S4: Vaporizing the liquid. S1: Yeah, so the hot water in the bottom would basically just be cold water. S4: Exactly. And then there wouldn't be any liquid vaporized. S1: That's also what we saw in our experiment where we added cold water and that created less clouds, whereas adding more hot water created more clouds.
12 (Clouds)	S1: The hot water because there has to be some steam to bind on the... S4: Yeah, liquid, yeah S3: Yeah, and the cold water to make a temperature change in which the steam can form a cloud. S4: Yeah, and the cold water to make the saturation amount lower. S1: And the hairspray to make aerosol S4: Yep. S3: And then the dish soap so all the steam wouldn't just go on the.... S2: Condense on the jar S3: Yeah, exactly.
13 (Clouds)	S1: And what happens on Earth is that the hot water is the surface of Earth which can be hot and that's water typically and the water is also what is steam, what is making steam. S2: So the water condenses from the the Earth's surface and then it rises up and makes a cloud and when the cloud gets heavy enough it starts raining right S4: So the aerosol is dust, the soap and the container is... nothing. S2: Yeah, dust and pollution and- S3: It could be pretty much everything with a surface for the water to condense onto. S4: And the warmth is the Earth and then the cold is the upper atmosphere. S1: Yeah, exactly
14 (Clouds)	S2: So what happens on an exoplanet? S4: The exact same. Instead of it being water, it is some type of liquid

(Table continued)

TABLE II. (*Continued*)

No.	Excerpt
15 (Clouds)	[comparing the experiment to exoplanets] S4: So in exoplanets, instead of it being water, the vapor, it is usually some other liquid. S2: Yeah and it could be a gas as well S3: Or a metal
16 (Clouds)	[Reading the question]: Explain how you can relate what happens in the experiment to what you see here on Earth. [Talking to peers]: Well, maybe like there's [...] maybe there are small impurities in the air that sort of work as these aerosol particles, where like when the water... When the water vapor... Well, when the water evaporates, it will rise. Because we know hot things tend to rise, or cold things tend to... Whatever. And this water vapor will then perhaps condense onto small impurities or just particles in the air. We talk about dust and pollen as being things that can condense onto. So that's what we see on Earth. And yeah, what we see on Earth is water that is condensing. But what happens on exoplanets is that could be any sort of chemical or just liquid that can evaporate, can form a cloud, from at least what I've understood so far.
17 (Clouds)	S2: I don't think we did anything that wasn't necessary. Of course, like, the soap that was in the jar wouldn't actually be present in an atmosphere or like in... S3: But the soap... was just to like make it like the water doesn't like attach S2: But what I'm saying is that wouldn't actually happen in the atmosphere, so that would be unnecessary out there. It's just to represent how it works. Like in the atmosphere we don't have a jar. It's just air around. S3: yeah, of course, I mean the whole atmosphere is like the jar you know? S2: Yeah, kind of. But like, the soap isn't necessary here, because there's no, like... Well, I think you can get one in the shower. S3: We needed to soap just to see what was going on in the jar. S2: Yeah, no exactly. What I'm saying here is that the irrelevant parts of the experiment like not that that was irrelevant But it wasn't it wouldn't be necessary if you were just observing like the atmosphere or the clouds. S3: Oh, yeah S2: Up there... Yeah, you know
18 (Clouds)	S3: We used water vapor and a cloud seeder to make clouds. S2: Yeah, and aerosol. S3: Yeah thats the cloud seeder S2: Oh, okay. Cloud seeder, yeah. Yeah, and that created clouds in a jar. S3: Because clouds need something solid to bind onto. S2: Yeah, the water vapor has to bind to a surface and that S3: solid surface so we use our aerosol. S2: Aerosol works as the binder or the surface to bind to which then visualizes the cloud yeah.
19 (Clouds)	S2: No, we put the dish soap on the side and that was to stop it from sticking to the sides of the jar. S1: Yes, and make it... S1: The vapor. It didn't really like interfere with the experiment at all. It just made it.. S2: It prevented it.. S1: It made it easier to see for us
20 (Clouds)	S1: I mean all the different parts could be related to different elements of the Earth. For example the cold water at the top of the jar would be the outer atmosphere, where it's obviously colder. S2: Yeah, the hot water at the bottom could be the heat radiated from the Earth. Yeah, so it's warmer on the ground. Yeah, the surface temperature. S4: also the aerosol could be like dust. S2: Yeah! So instead of the Earth being covered in hairspray, it would be dust particles to stick to, which is... yeah.. why we get the clouds we have here. S1: And it also asks what happens on an exoplanet where it's basically the same because I mean they have the somewhat same elements as on the Earth. S2: So, well, I mean, it's a bit different because. You know, on Earth we have... S1: Yeah, of course. S2: Yeah. How do you explain that? So on Earth we have like water and the ground's like... I guess there'd be more heat out of it.
21 (Clouds)	S1: I mean we can relate that, right? I mean we did an experiment where we created a cloud. S2: So these conditions are what create clouds generally in any environment. So if there's a difference in temperature and uh... If there's some sort of vapor, either if it's water or any other gas, and if there's like a structure... like an aerosol it can stick to then there'll be clouds.

(Table continued)

TABLE II. (Continued)

No.	Excerpt
22 (Clouds)	S2: I guess the dish soap is kind of irrelevant to the experiment itself because the only thing that really did for us was to visualize so we could better see the cloud S1: Yeah, make it more visible. S2: because if we didn't add the dish soap then the cloud would still form but we would just not... be able to see it as well. S1: Yeah, we would just see the jar getting f****ed yeah S2: Yeah, and generally it didn't mess with the experiment. Like adding dish soap didn't do anything to the cloud. So I guess thats irrelevant
23 (Clouds)	S2: The side of the planet that's facing the star at all times is very, very hot at the surface because of the planet, and also very hot at the top of the atmosphere. Like the atmosphere. S1: It would be like doing this experiment without the cold water. S2: So that wouldn't have clouds. But on the cold side where it's constantly dark, there's no sun to heat up the outer atmosphere. so that's the cold water.
24 (Clouds)	S1: I dont know how the hairspray works was that the.... S2: No, that was the... S1: The aerosol? - S2: Yeah. The little... uh... dust stuff. So that's what the solid that the molecules, S3: They need the solid to make the clouds.. S2: to fasten on and make the cloud. S1: To make sure that it doesn't happen to the surface of the jar, to both visualize it and for it to happen to the clouds, we're going to use dishwashers soap.
25 (Clouds)	S3: What happens if its an exoplanet? S2: Oh, what's [their] name? Oh, [scientists name] Yeah. [they] spoke about the other kind of materials being in the air, the exoplanets. Yes. So it's the same thing that happens, but with other particles. S1: I'm not sure but I think that's how acid rain is created because it's vapor from acidic liquids. S3: [they] also said it was metals right? S1: Metallic vapor. Yeah, I think that's probably acidic as well, because I don't know, it may be this. S2: Yeah. Acid rain?. And something that's metallic. I'm not sure about that. Okay. S3: I think acid rain is when rain falls and it picks up pollution. And I'm pretty sure in India they use very dangerous chemicals to create clothes and... S1: That might be the vapor maybe. Yeah. But I don't know. It's one of those, but I think it's the vapor. S2: So the chemicals are the aerosols? S1: I believe it's the vapor being acidic to begin with and not when it's going down. S3: Yeah, but I think it's the solid and the aerosols. I don't know. And I'm not sure.
26 (Clouds)	S2: do you feel that the experiment changed or added to your understanding of cloud formation? S1: It did, because it visualized it for us. S3: The solid, the aerosol. Yeah, the aerosol. Was necessary. I didn't know. Yep. S2: I don't know that.
27 (Clouds)	S1: It is predicted that these planets will often have only clouds on one side. Why do you think this might be? It's pretty obvious, I think. S3: Yeah, because the ground needs to heat up to make a cloud. S2: Yes! Like we drew here [points to experiment diagram], the sun needs to heat up the ground.
28 (Lightning)	S2: I understand everything, but I would also say I didn't really know what the pencil was for. S1: The pencil also wasn't quite needed and the reason for that is because we had the rubber gloves also. Because the only reason for the pencil was that way we could move it onto the polystyrene without touching it and so we wouldn't discharge it instantly. S2: Yeah, so if we had... S1: But because we have the gloves on, that didn't really... Yeah, that didn't matter. S1: Although it's still good to do as precaution, like two layers of protection is better than one. S2: Let's say if it was a bigger experiment and you could actually get real electrocuted, then I would see it would be useful. S1: I mean, it's more like if it discharges while you're still moving it onto the... Of course, like nothing's gonna happen when you move to the front, because the charge is already on. S2: Yeah, so that would just kind of destroy the experiment. S1: So I wouldn't really say that in irrelevant parts. S2: It can change, like you can just have gloves on or you can take the gloves off and use the pencil. So it's something that can be... S1: Or you can do both at the same time.

(Table continued)

TABLE II. (*Continued*)

No.	Excerpt
29 (Lightning)	S1: We were talking about the convection, we need the updrafts for the molecules to really move around in the atmosphere. While on the cold side, there would only be the downward force, there would be no upward force, so there would be no rubbing together of atoms. S2: So we wouldn't need like...
30 (Lightning)	S1: There might be lightning, but it would be very rare. S3: Yeah, plastic. We rub the plastic one with wool for two minutes and put the metal on it. S1: the metal container on the plastic container and then S3: I've got a fork close to the metal container too. S1: make thunder, a thunder sound. S2: And lightning
31 (Lightning)	S1: The positive will get close to the negative. Yeah, so... The negative... S3: most close.. S1: will be in the top of the metal container. So when you have the fork besides the metal container in the top, the fork is neutral and the positive will be at the end you—Yeah. S3: half close to the metal.. S1: Half closed to the metal container, so it will be negative and positive together and that makes thunder.
32 (Lightning)	S3: When there are two clouds, one is very positive and one is very negative. S1: no...It was more like... S2: They split up, like the metal container. So like the bottom got negative and the top got positive because of like big and small things inside the cloud S3: When another cloud also comes, it makes the opposite of what is closest to it. S2: yeah, The cloud coming is like the fork... S3: So there will be a positive and a negative end of the clouds and then it makes lightning
33 (Lightning)	When [lightning] happens on the exoplanet, it's actually a little bit the same as on Earth
34 (Lightning)	S2: Are there confusing or irrelevant parts of the experiment? If so, which parts are... and why? S1: Are there confusing or... S3: Maybe the pencil. S1: Oh, yeah, but it was just to hold, so you didn't have to touch it. S3: Yeah, but we have gloves on S1: yeah, I don't know, maybe because the one who has to hold the fork and the metal thing shouldn't have gloves on because
35 (Lightning)	S3: Maybe the pencil. S1: Oh, yeah, but it was just to hold, so you didn't have to touch it. S3: Yeah, but we have gloves on S1: yeah, I don't know, maybe because the one who has to hold the fork and the metal thing shouldn't have gloves on
36 (Lightning)	S3: But I didn't understand the pencil. S1: No, I didn't understand what the pencil ok, [the teacher] just said to us... S2: I think it was just because we didn't touch the metal container...
37 (Lightning)	Maybe it's a little bit weird that after you have touched it, it gets one lightning, there can't be another one until you recharge the plastic container. That's a little bit weird.

APPENDIX B: CODING MATRIX

TABLE III. Excerpt coding matrix, where each row corresponds to one of the excerpts in Appendix A and each column corresponds to one of the categories detailed in Table I.

Excerpt	Phys	Earth	Exop	Exp	1a	1b	1c	1d	2a	2b	3
1				x				x			
2	x			x					x		
3	x	x				x		x			
4		x			x						
5			x		x		x				
6	x			x	x						
7		x						x			
8	x		x				x	x			
9		x	x		x		x				
10									x		
11			x	x	x		x				x
12	x			x	x	x		x	x		
13	x	x		x	x	x			x		
14			x	x			x	x			
15			x	x			x	x			
16	x	x	x	x	x	x	x				
17	x	x		x					x		
18	x			x				x			
19				x					x		
20	x	x	x	x	x		x				
21	x	x		x				x			
22				x					x		
23	x		x	x			x				x
24	x			x				x	x		
25	x	x	x	x			x				x
26				x				x			
27	x		x	x		x	x				x
28				x						x	
29	x		x								x
30				x				x			
31	x			x				x			
32	x	x		x	x						
33		x	x			x	x				
34				x						x	
35				x						x	
36				x					x		
37				x				x			

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