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Students' Understanding of Analogy after a CORE (Chemical Observations, Representations, Experimentation) Learning Cycle, General Chemistry Experiment

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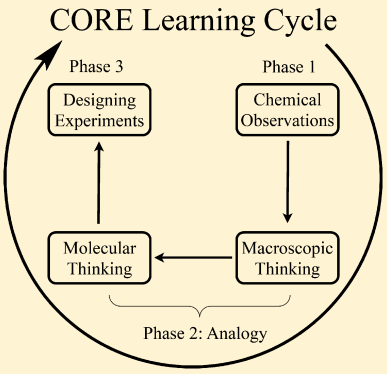
Supporting Information

ABSTRACT: Students' understanding about analogy was investigated after a **CORE** learning cycle general chemistry experiment. **CORE** (**C**hemical **O**bservations, **R**epresentations, **E**xperimentation) is a new three-phase learning cycle that involves (phase 1) guiding students through chemical observations while they consider a series of open-ended questions, (phase 2) developing representations using analogical thinking, and (phase 3) designing and conducting experiments in response to a scientific question. In the **CORE** experiment used in this study, Polymers and Cross Linking, an analogy was employed in phase 2 when students reflected on the similarities and limitations between objects used in the analogy (the analog) and the chemistry under observation (the target). Owing to the reliance on analogical reasoning in the **CORE** approach, we conducted a study at a single point in time at the very beginning of a lab course to investigate students' understanding about analogy, the importance of considering the limitations of an analogy, and perceived benefits. Four online questions were asked approximately one week after lab work. Student responses (n = 501) across the four questions provided a rich data set of over 60 000 words (averaging >120 words/student). Results indicate that 75% of students have a basic or better understanding of the analogy, 61% of students connected the analogy with either chemical observations from lab and/or submicroscopic thinking, while 8% connected the analogy to both. A majority of students (57%) described the importance of appreciating the limitations of an analogical model and numerous students offered details about how analogy influenced their conceptual understanding. The data provide insight into student understanding about analogy and the degree to which students recognize the limitations of an analogy, as well as student perceptions of the benefits of the approach. This study informs those interested in developing curricula around the **CORE** approach and suggests design criteria for investigating student learning when analogies are used as part of lab work.



KEYWORDS: *First-Year Undergraduate/General, Laboratory Instruction, Chemical Education Research, Analogies/Transfer, Inquiry-Based/Discovery Learning*

FEATURE: Chemical Education Research

INTRODUCTION

In the past decade, there has been an increased emphasis on replacing standard laboratory courses with those that engage students and reflect the nature of inquiry (e.g., 2012 PCAST report).[1] Inquiry in chemistry is driven by the centrality of making connections between the macroscopic and submicroscopic levels to understand chemical observations, plan experiments to test new ideas, and interpret data that arises from atomic level phenomena. All aspects of inquiry are enhanced by using analogical reasoning to form representations of the atomic and molecular level, which can be refined over time as more information is accumulated. In fact, from a theoretical perspective it can be argued that thinking about chemistry necessitates analogical thought.[2] Niebert, Marsch, and Treagust have emphasized the importance of analogies in science (ref 2, p 849):

> *(o)n the basis of the theoretical framework of experientialism, we argue that not only teaching but also thinking about and understanding science without metaphors and analogies is not possible.*

In *Making Truth: Metaphor in Science*, T. L. Brown asserts that teaching science

> *involves imparting conceptual understanding and a sense of intellectual excitement about the subject. The creative use of metaphor is a vital element in that process.*[3]

Given the necessity of using analogical reasoning in chemistry, we suggest that in order to achieve higher levels of inquiry, we should provide a framework for our students to acquire and practice the skill of analogical reasoning in the laboratory. However, student capacity to understand analogical thinking as

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part of laboratory work and the supports needed to effectively build this skill in a large introductory course setting are not well understood.

Thinking critically about chemistry at the atomic scale (submicroscopic level) while making chemical observations in the lab (at the macroscopic level) is very challenging for many of our beginning chemistry students. Similar sentiments have been shared in the literature.[4−7] This lack of skill can create a frustrating experience for our students in an inquiry-based lab when they are asked to design appropriate experiments and procedures to explore specific scientific questions. The literature on discovery-based learning,[8] as well as factors that are important for facilitating and supporting inquiry,[9−11] suggests that structure and scaffolding are essential in introductory laboratory learning environments to help facilitate critical thinking processes.

From these considerations and with guidance from the theories related to analogical reasoning,[12] we have been exploring ways to anchor analogical reasoning to the laboratory experience.[13] Recently, we have developed the **CORE** learning cycle (**C**hemical **O**bservations, **R**epresentations, **E**xperimentation),[14] which provides a three-phase process for introductory students to engage in chemical laboratory experimentation. In phase 1, students make chemical observations in the lab and are prompted by open-ended questions to begin thinking about the underlying chemistry. In phase 2, students engage in structured analogical reasoning activities to build and refine representations. In phase 3, students design and carry out experiments in response to scientific questions.

A novel feature of **CORE** occurs in phase 2 when students pause between making chemical observations and designing experiments to engage in an analogical reasoning activity. The analogical reasoning activity could employ concrete, hands-on objects or other representational models. The purpose of this phase is to provide students with a strategy to develop skills for connecting chemical observations at the bench scale with the chemistry at the atomic scale. Research has been conducted on the use of analogies in classroom teaching and in textbooks, and what has emerged from these studies are aspects of teaching with analogy that should be present for their effective use (vide infra). One critical feature of student construction of an analogy is reflection on the similarities and limitations between macroscopic and atomic scales. Given the reliance on analogical reasoning to the **CORE** approach, we wanted to understand students' thinking about analogy in the context of a **CORE** experiment. We therefore designed a study to investigate the following research questions:

1. What do students understand about analogy and what connections do they make to chemical observations and submicroscopic thinking?
2. What do students think about the importance of considering the limitations in an analogical model?
3. What are student perceptions of the benefits of analogy as well as their reservations?

The study was aimed at establishing an initial reference point (i.e., a snapshot) to assess what our students understood about analogy after a single **CORE** experiment. The data set (n = 501) was constructed from student responses to online questions, which were answered about 1 week after lab experimentation had occurred. Student responses were parsed in different ways (vide infra) to analyze the research questions listed above. Thus, we did not examine prior knowledge or attempt to measure student growth that might have occurred with the **CORE** experiment. Rather, our intent was to gather data that would provide guidance on curriculum development using the **CORE** learning cycle approach and inform the design of further studies to investigate the influence of **CORE** experiments on student learning. Previous studies by Treagust et al. describe students' understanding of models at a point in time when students have not yet been exposed to any special teaching about scientific models beyond the general science curriculum.[15,16] Our study describes students' understanding about analogy in a chemistry experiment on polymers and cross-linking (see Supporting Information for a summary of the lab experiment). The results inform a practical and theoretical understanding of students' learning with analogies in the laboratory environment.

This project is part of a larger NSF-MSP project (see acknowledgments), one component of which involves reform of university STEM courses, including introductory chemistry, and aligns with the suggestion in the 2012 NRC DBER report that these courses "...provide the most effective overall learning experiences to help students acquire greater expertise in their disciplines".[17]

THE TEACHING WITH ANALOGY MODEL AND ANALOGY STUDIES

Analogy is a mode of representation that is used to explain scientific concepts and can be considered a subset of models.[18−20] Analogies are useful for teaching abstract concepts, which are "difficult for students to construct through direct experiences, such as labs and demonstrations". Furthermore, they can help students build and revise mental models,[21] leading to restructuring of scientific knowledge and conceptual change.[22,23] Comparing an unknown domain with a familiar one[19,24] can set up an opportunity to help students engage with a concept from a different viewpoint.[25,26]

Analogies and models are frequently used in science and students are exposed to them all the time in a variety of STEM learning contexts. A number of authors have noted variable outcomes in studies on the effectiveness of analogies in textbooks or the classroom.[19,20,24,27−29] Some authors have argued that this is mainly due to the way analogies are being introduced to students and that analogies can be effective if they are clearly presented within frameworks such as the Teaching with Analogies Model.[27,30−32] Since analogies have the potential to be misleading, there is a need for students to practice analogical reasoning in order to avoid additional misconceptions.[19] Asking focused questions about features that are not shared between the target concept and the analog can reduce the incidence of misconceptions.[31] Specifically, students must develop analogical reasoning skills and be shown explicitly how to use analogies and models.[33]

Orgill and Bodner interviewed students on the usefulness of analogies, asking them what they needed in order to learn well from analogies.[26] Most of the students found the analogies beneficial but gave a variety of reasons for their effectiveness, including helping them understand concepts or phenomena that cannot be seen with the naked eye. Students felt that good analogies are simple, easy to remember, and familiar. Students also said that they would like the instructor to explain the purpose for using the analogy and the relationships between the analog and the target concepts. Brown and Salter's literature review summarizes the three most important elements to focus on when teaching with analogies: to talk explicitly about the analogy; to use well-developed analogies; and to explain the structure and limitations of the analogy.[33]

Analogies in chemistry are often used to make the submicroscopic nature of molecules and molecular processes

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more tangible. For example, Kolb and Kolb describe a classroom analogy for polymerization that uses students as monomers and then has them link hands to demonstrate the process of polymerization.[34] Nassiff and Czerwinski[35] describe how the use of large and small paperclips to model atoms and to present Dalton's atomic theory yields a deeper understanding of the concepts. In both of these cases, however, limitations of the model were not discussed. In addition, textbooks usually do not emphasize explicitly mapping connections between the analog and the target, similarities or dissimilarities between them, or conclusions that can be made about the concept after students are exposed to the analogy.[19,20] Ignoring the limitations of an analogy can have a negative impact on learning.[33] In order for an analogy to be useful, students need to be able to discuss and critique the analogies, as a way for them to reflect on their own scientific understanding and refine their mental model.[18,33,36]

THE TEACHING LABORATORY AND ATOMIC SCALE (SUBMICROSCOPIC) THINKING

The laboratory is the primary place where students can safely interact with chemicals, make observations, and gather data. Lab work is essential to science education because it provides students with opportunities to learn about science process and science content.[37] However, there is often a disconnect between the procedural level where macroscopic observations are made and students' abilities to imagine the molecular level processes that occur in the flask.[5]

In 1991, Johnstone discussed the challenge for teachers in helping students make connections between macroscopic and submicroscopic realms. He presented a "levels-of-thought" triangle with the macro, submicro, and symbolic[s] components of chemistry at the vertices of a triangle.[6] (In a subsequent, highly cited article in this *Journal*, the word representations replaces symbolics.[38]) Johnstone argued that students are not helped when "...the teacher uses macrophenomena to pull the pupil, almost instantly into the middle of the [levels-of-thought] triangle...".[6] By the middle of the triangle, Johnstone means the ability to build reasoning about and make connections between the three corners of the triangle (also see ref 39). Yet this is a worthwhile undertaking because integration of molecular representations can enhance students' understanding in the submicroscopic domain.[40−42]

The mental model students have of submicroscopic phenomena is a result of their conceptions and understanding of multiple representations and models of the submicro level.[18,40,43] Part of the difficulty that students face when making connections between macroscopic and molecular thinking is a lack of skill in using representations and models. It is important to design learning environments in the lab that foster meaningful learning by integrating representations; this is also recommended for learning environments outside the context of the lab.[44−46] Tan et al. claim that in most cases, students do not think about the submicroscopic level of phenomena while doing lab activities and they do not connect the submicroscopic level to the macroscopic level.[4] The **CORE** learning cycle was designed to help students build skill in making these connections. In the next section, we discuss the use of analogies to further integrate these levels of thinking.

ANALOGICAL REASONING AND THE LABORATORY

Engaging students in analogical reasoning refines their mental models to be more in agreement with conceptual models shared by the scientific community.[19] Duit and Glynn specified the advantages of using analogies, claiming that analogies can provide new perspectives and therefore are valuable for conceptual change, can promote abstract understanding, and can enhance students' interest and motivation.[19] By moving analogical reasoning activities into the realm of the laboratory, we provide students with the opportunity to connect experimental results to the modeling process. This affords students the opportunity to use the analogy in thinking about chemical phenomena that occur at the atomic scale.

As described in *America's Lab Report* by the NRC,[37] connecting lab to other activities such as discussions and explanations is valuable to achieve meaningful understanding.[37] The NRC report recommends using animations or analogies to help students explain and connect macroscopic laboratory observations to the submicroscopic chemical concepts. Likewise, Tan et al. recommended the use of analogies or animations while carrying out an experiment in the lab to help students explain and connect the macroscopic level to the submicroscopic level.[4]

The **CORE** learning cycle is a strategy to introduce analogical reasoning activities systematically into the general chemistry lab curriculum to help students relate their "hands on" lab activities and observations to the theoretical models that underlie sense-making in chemistry. *For the purposes of this paper, we define analogical reasoning as thinking processes used to compare and contrast chemistry occurring at the atomic and macroscopic levels (or domains) that is under investigation by students in the laboratory.* For a quarter of a century, research has identified features for effective use of analogy, and bringing analogy into lab requires attention to these features, which are summarized here: the analogy should originate in a domain that is familiar to the student (the analog); the analogy should connect to a domain sufficiently demanding (the target); similarities should be explicitly considered (correspondences); limitations should also be explicitly considered (where the analogy breaks down); and the analog and target should share deep structural similarities not surface features.[26,27,30,47−50] Curriculum development within the **CORE** learning cycle affords the opportunity to introduce laboratories subscribing to these features. An expanded discussion of theoretical motivations for designing the **CORE** learning cycle,[14] as well as examples of **CORE** experiments, will be reported elsewhere.[51]

STUDY CONTEXT

The ongoing project involves an effort to reform the laboratory curriculum in introductory general chemistry at the University of Maine, a small research-intensive (RU/H, Land and Sea Grant) institution. About 700 students took the first-semester general chemistry course and 501 students consented to participate in the research in this UMaine IRB approved study during fall 2011 and spring 2012. Students answered four open-ended questions online using the InterChemNet course management system developed at the University of Maine.[52] The data were collected after students had completed an initial **CORE** laboratory experiment called Polymers and Cross Linking. A summary of the **CORE** lab used by students is provided in Supporting Information. Further details concerning the analogy activity are also provided here. In phase 2, students construct an analogy by using black and white paper clips. The activity is designed to parallel the wet chemistry performed in phase 1. Student construction of the analogy involves completing an Analog to Target Worksheet that explicitly asks students to consider similarities and differences between the analog and target, and

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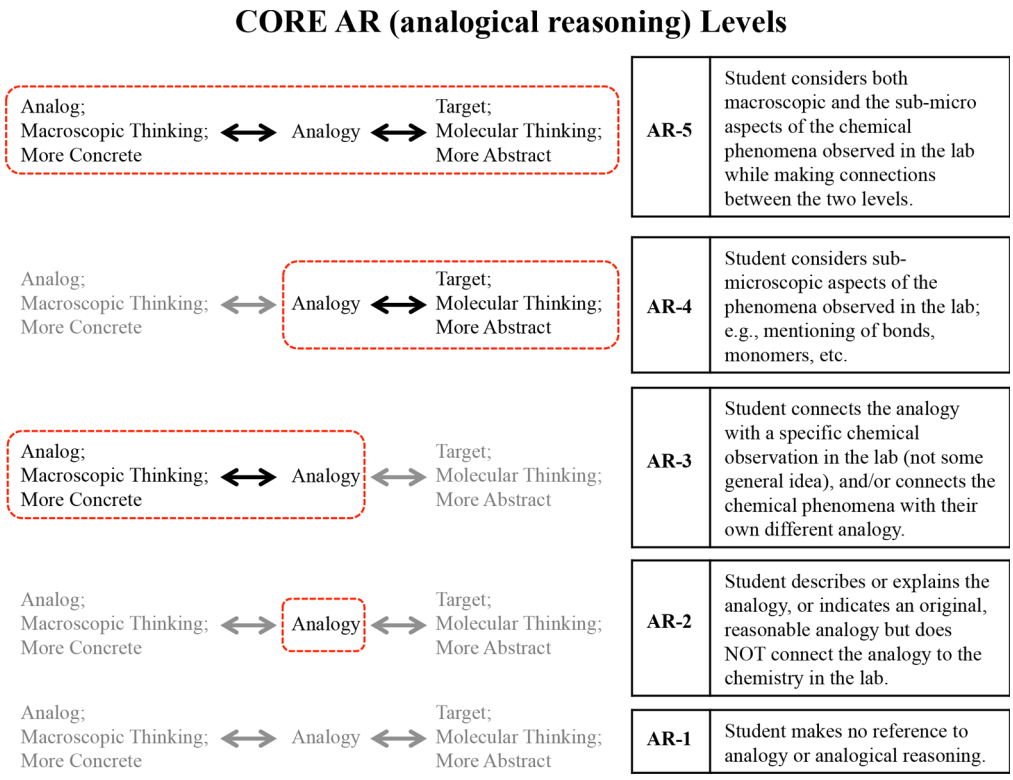

Figure 1. A tiered framework for understanding an analogy (left side), and the rubric (right side) used to interpret student analogical reasoning (**AR**) levels. Student responses across all four questions (**Q1**−**Q4**) were used to assess the level of **AR**. The grayed out writing on the left-hand side indicates a deficit in understanding.

includes a place for a molecular drawing to illustrate comparison between the product of the chemical reaction of poly(vinyl alcohol) and sodium borate, i.e., slime, and the "product" of linking white chains with black paper clips. (See Analog to Target Worksheet in Supporting Information.) This analogy is designed to promote student development of higher-order relations through correspondences that focus on how the structure of the materials in the two domains influences the properties of the materials. In reflecting on the noncorrespondences in the analogy, students consider the limitations of the analogy, such as the differences between chemical and mechanical interactions, and links in the polymer and paper clips, respectively. On a macroscopic level, the analog conveys why liquid polymers combine to form a viscous putty. On a molecular level, the analogy emerges through structure−reactivity relationships.

■ GOALS, METHODOLOGY, AND DATA COLLECTION

The goals of our study were to investigate student thinking about three aspects of analogy: (a) understanding of analogy, including what connections students make to chemical observations and/or submicroscopic thinking; (b) the importance of considering limitations in an analogical model; and (c) thinking about the benefits of using an analogy as part of lab work. Our research questions, presented in the Introduction, were designed to explore these aspects.

To collect data, we asked students a series of four questions (**Q1**−**Q4**) about analogy after they completed the Polymers and Cross Linking lab experiment. Students encountered the questions as they logged into their InterChemNet accounts to download the next week's lab procedure. Please note that as described below, there is no one-to-one correspondence between the research questions and the questions (**Q1**−**Q4**) asked of students.

Q1: "Do you agree or disagree with the following statement? An analogy can help in describing the invisible chemistry and concepts one can't see. Please explain."

Q2: "Is there another analogy that you can think of that would help you gain insight into the chemistry involved in this lab? Please explain."

Q3: "Is it important to think carefully about where an analogy breaks down, when using analogies? Please explain."

Q4: "Did you find the analogy beneficial to your understanding of the concepts being learned in this lab? Please explain."

While many questions are phrased as binary choices (i.e., agree/disagree or yes/no), they all ask for explanation. The more open-ended portion of the questions formed by the request for an explanation generated the information we analyzed. We expected that student responses to **Q1** would allow us to capture information about understanding of analogy as well as the spontaneous connection of the analogy with laboratory work or submicroscopic phenomena. **Q2** was an interesting question for us in that the answer requires a student to analogically reason to construct an answer, i.e., to compare the analogy used in lab to another analogy. In addition to identifying other analogies that students found to be relevant, we thought that this information might provide additional evidence about student understanding of analogy. **Q3** was asked because the literature suggests that consideration of the limitations of an analogy is a critical step in effective use of analogies. The wording of **Q3** was constructed in parallel with the teaching with analogies model, as in "Indicate where the analogy between the laws breaks down".[31] **Q4** was asked to gather information about the benefits of analogy. We expected that the words students chose would provide additional insight into what they understood about analogy, what benefits of

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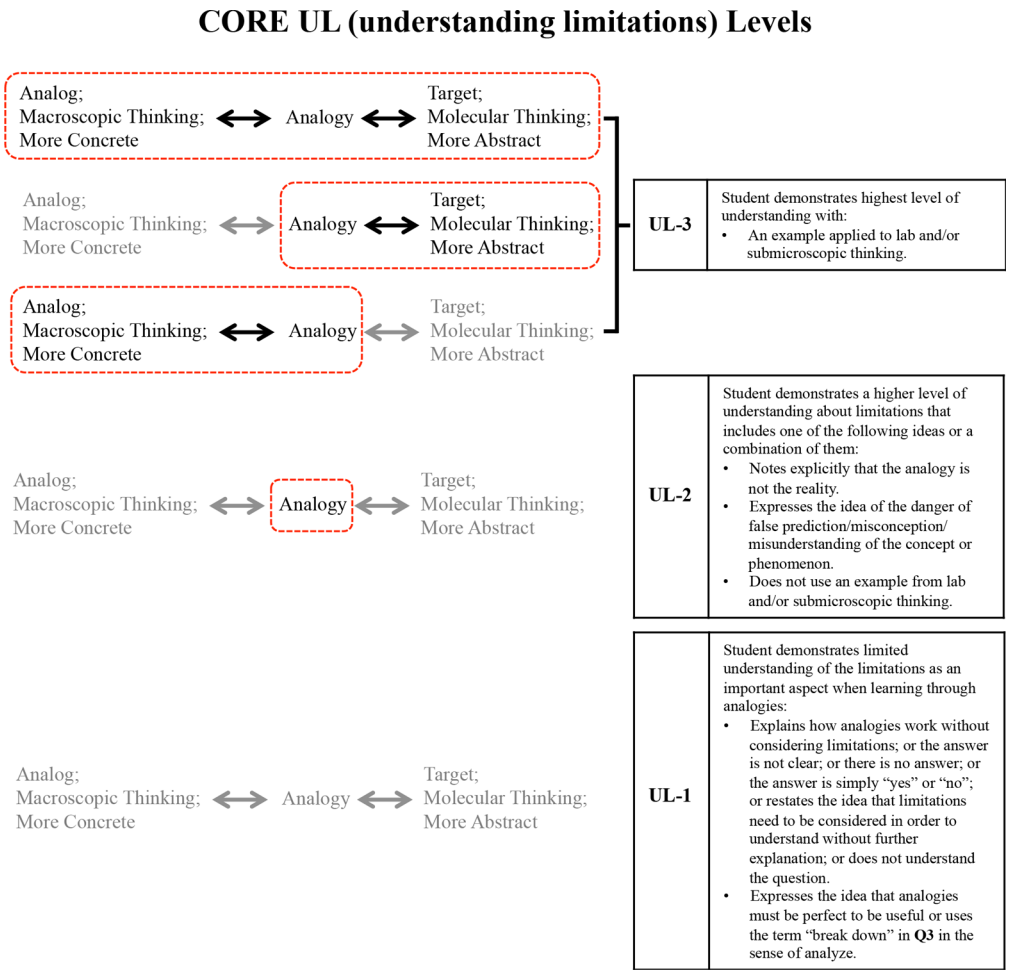

Figure 2. A tiered framework for understanding the importance of considering limitations in an analogy (left side) and the rubric (right side) used to interpret student understanding of limitations (**UL**) levels of an analogy. Student responses to **Q3** were used to assess the level of **UL**. The grayed out writing on the left-hand side indicates a deficit in understanding.

analogy they perceived, and to provide clues about the affective dimension. The last point is based on the idea that students who did not like the approach or did not engage with it may describe why it was not beneficial. Student responses (n = 501) across all four questions provided a data set of over 60 000 words (averaging >120 words/student). For comparison, this is equivalent to over 240 pages of writing, containing 250 words/page. There was also tremendous range in the responses, from 3 to 660 words. We note that instructions for students included the following: "Your answers will be confidential and will not be used as part of your grade."

Research Question 1

To investigate student understanding of analogy, we combined responses to all four student questions, **Q1**−**Q4**. This allowed us to construct a profile to represent the extent of student understanding about analogy and the degree to which students make connections between the macroscopic (chemical observations) and submicroscopic (atomic-level phenomena). We recognized that the profile would help assess student capacity to engage in the **CORE** experiments and would have significant implications for the approach. For example, if the profile showed that the average level of understanding of analogy was very low, then it may be suggested that students would find it difficult to integrate analogical thinking into lab work, while a very high understanding would suggest that understanding analogy would not be a barrier. To construct the profile, we developed tiered levels of understanding of analogy, presented on the left side of Figure 1. We also developed a rubric (presented on the right side of Figure 1), to judge attainment of these levels. We have based our rubric on the structure mapping theoretical construct,[12] in such a way that the focus of the analysis is on the relations between domains and not on the relative number of shared and nonshared features. Features that are not relevant to a mapping between domains (e.g., features like shape and color) are left behind during the analysis leaving higher order relationships, referred to as systematicity. These higher order relationships are the essence of the meaning in the analogy.

AR-3, **AR-4**, and **AR-5** are the relations formed by students in deriving meaning for the analogy. The highest level, **AR-5**, is associated with a student's recognition that molecular structure influences reactivity. Furthermore, the rubric categorized how students thought about the analogy as well as their thinking of a new analogy. There is a difference between using/interpreting analogies and generating analogies; however, both are related to analogical reasoning. Duit and Glynn[19] said "there are two ways in using analogical relations in modeling process; provide students with the analogy or help students construct their own analogies". The latter were also termed "self-generated analogies" when students construct analogical relations with minimal guidance. This is why students were judged to have attained

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Table 1. Examples for AR1−AR3: Student Verbatim Responses with Coding Notes and Scores

Student's Level of Analogical Reasoning (**AR**)	[Rubric Description] Student Answers
Level **AR-1**.	[No reference to analogy or analogical reasoning was made.]
Student 12380:	(**Q1**): *I agree because it helps put it in terms more easily understandable.*
	(**Q2**): *I can't think of anything that would make a good analogy and help me more with this lab.*
	(**Q3**): *Yes because without understanding where it breaks down you can't fully understand how the analogy works.*
	(**Q4**): *I felt that the analogy we used in class was helpful to make it easier to understand what was going on since I hadn't taken a chemistry class before.*
	Notes: The student restated what was asked in the questions without further explanation.
Level **AR-2**.	[Described or explained the analogy, or came up with an original, reasonable analogy but did NOT connect the analogy to the chemistry in the lab.]
Student 12327:	(**Q1**): *Concepts in chemistry are abstract, analogies help relate everyday situations or objects to the abstract ideas in chemistry.*
	(**Q2**): *People in line at a box office filing single file into separate doors, suddenly the people hold hands and they can't fit through the doors.*
	(**Q3**): *Yes, if you don't pick an analogy correctly, someone may find a gap in it where they may think of something else when reminded of the analogy.*
	(**Q4**): *Yes, I found the analogy very useful, without the paper clips being shown, I would not have any visual representation of the chemical reaction in my head which would have made it harder for me to understand.*
	Notes: The student describes how the analogy is beneficial and came up with an analogy but did not connect the analogy to the chemistry in the lab.
Level **AR-3**	[Connected the analogy with a specific chemical observation in the lab (not some general idea), or Connected the chemical phenomena with their own different analogy.]
Student 12280:	(**Q1**): *because in the lab we just did we couldn't really tell what happened when the polyvinyl and the borate mixed together. We could see that they formed a new substance but we couldn't see what was actually happening. When we used paper clips we could see that the polyvinyl alcohol chains were connected by the sodium borate forming a new substance.*
	(**Q2**): *One analogy could be a train···because a train is also like a chain. When more and more carts get added onto the train the longer it takes for the entire train to pass through a certain place. Like with the "slime" it takes a longer period to pass through the funnel than the polyvinyl alcohol and the sodium borate do separately. The train unattached to the carts can pass more quickly by things.*
	(**Q3**): *you have to know how the analogy is similar to the actual polymer and where it is different so you can actually understand the process taking place.*
	(**Q4**): *I could see that when combined the polyvinyl alcohol and the sodium borate made a new substance but I didn't really know how that happened. So when we used the paperclips I could see that the sodium borate molecules were connecting the chains of the polyvinyl alcohol solution, causing a new substance to form.*
	Notes: The student is making connections between the analogy and the specific chemistry in the lab.

AR-2 or **AR-3** levels if they used either of these two strategies for analogical reasoning. For coding student responses, a process of inter-rater reliability was conducted. Two researchers independently coded samples (e.g., 10% of students) followed by refinement of the rubric and discussion of coding considerations. Then, a second round of coding was conducted that included all student responses, resulting in agreement of well over 85%. All remaining cases were adjudicated. The final rubric used is shown in Figure 1.

The **AR-1** level showed no evidence of understanding of analogy. We considered a basic understanding of analogy was attained (**AR-2**) when student responses described or explained how the analogy worked, i.e., through a comparison across domains, or by describing another reasonable analogy. Higher levels of analogical understanding were attained when students demonstrated basic understanding plus inclusion of the connection with the following:

- the macroscopic level of the analogy (**AR-3**),
- the submicroscopic level (**AR-4**),
- both macroscopic and submicroscopic levels (**AR-5**).

Research Question 2

To investigate student thinking of the importance of considering limitations in an analogical model, we analyzed student responses to question **Q3** using grounded theory.[53,54] An open coding protocol was used by two researchers to create a set of codes from the entire data corpus in order to generate new insights regarding students' understanding of limitations of analogies. The emergent codes were discussed and cross-checked to establish a common set of codes (i.e., a rubric) and then grouped to form categories and subcategories.[53] Subsequent rounds resulted in agreement of over 90%, followed by a meeting where all differences were adjudicated.

Figure 2 places the understanding of the limitations of an analogy (**UL**) upon a tiered framework of analogy parallel to that used for **AR** levels. A low-level of understanding of the importance of considering limitations is referred to as **UL-1**. This collects together students who were coded as either they did not consider limitations, simply answered yes or no, restated the question, did not understand the question, thought the analogy needed to be perfect to be useful, or interpreted the words "break down" to mean a strategy for analyzing the components of the analogy, rather than describing why it was important to consider limitations of an analogy. A basic appreciation of limitations (**UL-2**) collected together students who noted explicitly that analogy was not reality, expressed the idea of danger of false predictions, possible misconceptions, or misunderstandings of the concept or phenomena if the limitations were not considered, but did not make any connections to either side of the analogy. The higher level of understanding (**UL-3**) included a basic appreciation of limitations supported by examples of connections, i.e., to macroscopic and/or molecular thinking, and was created by combining the different types of higher order connections into a single category (**UL-3**) owing to the much lower frequency in this level (vide infra: 15% for **UL-3** vs 61% for the higher **AR-3−5** levels). This process of open coding and refinement of our codes enabled us to create a theory from the data (see Figure 2), and use our categories to further advance the theory on students' understanding of limitations.[55,56]

Research Question 3

To investigate student perception of the benefits to their understanding of the concepts being learned in this lab, **Q4** was analyzed by looking at evidence of students' description of benefits and concerns about analogies. The purpose of this question was to gain further understanding of a student's understanding of analogy and to elicit examples of perceived benefits, as well as reservations. Analysis included tabulating the different types of perceived benefits and reservations that were expressed.

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Table 2. Examples of AR4−AR5: Student Verbatim Responses with Coding Notes and Scores

Student's Level of Analogical Reasoning (**AR**)	[Rubric Description] Student Answers
Level **AR-4**.	[Student considers submicroscopic aspects of the phenomena observed in the lab; e.g., mentioning of bonds, monomers, etc.]
Student 12263:	(**Q1**): *I agree because an analogy is a comparison between two domains with which the analog concept is familiar, while the target concept it is compared to might be unfamiliar.*
	(**Q2**): *The analogy of cement mix to water is an example of the chemistry involved in this lab because there is a chemical reaction occurring with respect to the cement mix and water mixing. With the cement mix by itself, it is a powdery substance that can be poured easily; however, with the water combined forms a hard structure that can not be poured easily.*
	(**Q3**): *It is important to understand where analogies break down because if the analogy has a difficult time breaking down to a simpler concept, then the point of the analogy has lost its meaning. The purpose of an analogy is to take a complex topic and explain it in easier understanding. Thus, if an analogy can not be broken down into easier understanding then its purpose is lost.*
	(**Q4**): *I found the analogy of paper clips beneficial to my understanding in the lab due to the specificity of the topic it was able to demonstrate. Understanding how the individual molecules interact during the chemical reaction with respect to using paper clips as an analogy made he basics of what was occurring in the lab easier to see.*
	Notes: The student relates to submicroscopic level but not the connection between the macroscopic level and the submicroscopic level.
Level **AR-5**.	[Student considers both macroscopic and the submicro aspects of the chemical phenomena they observed in the lab while making connections between the two levels.]
Student 12294:	(**Q1**): *I agree with the following statement. Especially with chemistry, analogies are a good way to show the basic concepts using examples that we see each and every day. One would be, in the lab we did with the slime. The analogy of using the papers was a good one to show how the different molecules linked together and make the components more sturdy and less easy to pass through a small hole.*
	(**Q2**): *There is no other analogy that I can think of that would help gain insight in this lab.*
	(**Q3**): *It depends on how far the analogy goes and how descriptive of an analogy the chemistry concepts need.*
	(**Q4**): *I did find the chemistry analogy beneficial for my understanding. Using the paperclips helped me understand how the molecules within a polymer link together to form a much sturdier bond making it more dense and harder to pass through small spaces.*
	Notes: The student is making connection between the submicroscopic level and the macroscopic level and exhibits understanding of the connection between submicroscopic structure and macroscopic properties.

RESULTS

Analogical Reasoning (AR) Levels

Tables 1 and 2 provide representative verbatim student responses to **Q1**−**Q4** along with summaries of researcher notes, to illustrate how student responses were scored as **AR-1** to **AR-5** levels using the rubric shown in Figure 1. The results of analysis, shown in Table 3, indicate that 75% of students' responses (n = 501) exhibited a basic understanding (**AR-2**) or better (**AR-3**, **AR-4**, and **AR-5**) of analogy, with the remainder, 25%, not exhibiting understanding of analogy (**AR-1**). The results also show that 61% of student explanations include connections to macroscopic chemical phenomena (**AR-3**) and/or submicroscopic thinking (**AR-4** and **AR-5**). This total includes 25% of students who incorporated submicroscopic representations in explanations of analogy (**AR-4** and **AR-5**), with 8% of students who incorporated both sides of the analogy simultaneously, i.e,. from macroscopic to submicroscopic (**AR-5**). Further implications about **AR** levels are addressed in the Discussion section.

Table 3. Percentages of Students at Different Levels of Understanding of Analogy (AR)[a]

AR-levels	%
AR-5	8.2
AR-4	17.0
AR-3	35.7
AR-2	14.2
AR-1	25.0

[a] n = 501.

Understanding the Limitations (UL) of Analogy

To illustrate how student responses to **Q3** were scored regarding the limitations of analogy (**UL-1** to **UL-3** levels), verbatim student responses and research notes are shown in Table 4. The results of analysis, shown in Table 5, indicate that 58% of student responses exhibited a basic (**UL-2**) or better (**UL-3**) appreciation for an analogical model. The remaining 42.5% of student responses did not illustrate appreciation for the limitations of analogy (**UL-1**). This total includes responses in which students restated the idea that limitations need to be considered without further explanation (10%), described how an analogy worked (8%), or were not clear about their appreciation even if they indicated it was important (13%, e.g., "it's important because we should look at the analogy from every part"). Another category of student response was that for an analogy to be useful, it must be perfect (5%). This misconception has been reported,[18,57,58] i.e., that a model or an analogy needs to represent the reality exactly. Another 5% of students appear to interpret the phrase "break down" in terms of an analysis of the components of an analogy rather than the point at which an analogy stops working. Thus, one student wrote:

> *Yes, if you break down the analogy into parts it is much easier to follow the process of the chemical reaction. By breaking it down, you show all the steps and get a full understanding of what happens.*
>
> (Student 12686, **AR-1**, **UL-1**)

Finally, there were some students who did not appear to understand the question (2%).

Students who were judged to be at the basic level of appreciation (**UL-2**, 42.5%) fell into three categories: (1) those who thought incorrect inferences could be made if the limitations were not understood, (2) those who expressed that an analogy is not the reality, and (3) those who described details of the importance of considering an analogy's limitations. The students who were judged to be at a higher level of appreciation for the limitations of analogy (**UL-3**) also included in their explanation connections to laboratory or submicroscopic thinking. The differences and possible correlation between AR and UL profiles are explored in the Discussion section.

Student Perceived Benefit of Using Analogy with Lab Work

In **Q4**, students were asked if analogy was beneficial to their understanding of the concepts being learned in this lab. In addition to student responses being analyzed for understanding of analogy (i.e., **AR** levels), we looked qualitatively at student responses to

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Table 4. Examples of Verbatim Student Responses in the Different Categories of Appreciation of the Limitations of an Analogy

Student's level of Limitation Understanding (UL)	[Rubric Description] Student Answers
Level **UL-1**	[Student demonstrates limited understanding of the limitations as an important aspect when learning through analogies: • The student explained how analogies work without considering limitations; or the student's answer is not clear; or there is no answer; or the students just answered "yes" or "no"; or the student simply restated the idea that limitations need to be considered in order to understand without further explanation; or the student did not understand the question • The student expressed the idea that analogies must be perfect to be useful • The student used the term "break down" in Q3 in the sense of analyze]
Student 12273: **UL-1**	*Yes, I think that understanding exactly how the analogy works is the only way to truly understand what that analogy is trying to represent.* Notes: The student simply restated the idea that limitations need to be considered in order to understand without further explanation
Student 12339: **UL-1**	*If the analogy is off by a little bit, it will just put the wrong picture in your mind about the invisible thing that you cannot see. Therefore, you are not really receiving any insight about the lab or substance you are trying to understand better.* Notes: The answer conveys that the analogy must be perfect in order to be useful
Student 12411: **UL-1**	*Sure, you have to understand the analogy before you can understand the real concept. So breaking it down can help.* Notes: The term "break down" is used in the sense of listing components of an analogy
Level **UL-2**.	[Higher-level of Understanding – Student demonstrates a greater understanding about limitations that included one of the following ideas or a combination of them: • Note explicitly that the analogy is not the reality • Express the idea of the danger of false prediction misconception/misunderstanding of the concept or phenomenon. • Did not use an example from lab and/or submicroscopic thinking]
Student 12251: **UL-2**	*Yes, it is important to think about where an analogy breaks down when using them. No analogy is a perfect match to anything they are being used to describe. Sometimes really intricate problems cannot be completely described using analogies, so it is up to us to realize the holes in the comparisons and to try and fill them in with our own reasoning.* Notes: The students explicitly describes that the analogy is not the reality
Student 13064: **UL-2**	*Yes it is important to think of where an analogy breaks down. If you do not think of where it breaks down then you are getting a misconception of what the analogy represents.* Notes: The term "break down" is used in reference to the creation of misconceptions
Level **UL-3**.	[Highest-level of Understanding with • An example applied to either lab and/or submicroscopic thinking]
Student 12800: **UL-3**	*It is important to think carefully about where an analogy breaks down so that the concept and the invisible chemistry that is trying to be understood is not understood incorrectly. In this lab, there were only a handful of paperclips that were used, and these paper clips represented monomers, which created a polymer. In the actual chemistry of the combination of polyvinyl alcohol and sodium borate, there are millions of monomer subunits that make up the polymer. By using this paper clip analogy, one can easily think that there are only a few monomer subunits that are linked together to create a polymer. Although analogies can be very helpful in explaining an unfamiliar chemistry concept, it is important to make note of the differences between the analogy and the concept so that false information is not taught.* Notes: the explanation of limitations connects macroscopic to submicroscopic thinking

Table 5. Percentages of Students at Different Levels of Understanding of the Limitations of an Analogy (UL)[a]

UL-levels	%
UL-3	15.0
UL-2	42.5
UL-1	42.5

[a] $n = 501$.

gain insight into how students thought analogy was beneficial and for comments expressing reservations about using analogies. Almost all students answered affirmatively to **Q4**, and a majority of responses were accompanied by detailed explanations. It is noteworthy that benefit was perceived across the entire range of **AR** and **UL** dimensions. We illustrate this here with examples (student numbers and **AR** and **UL** levels are recorded at the end of each quote). Additional examples of student responses at these levels are supplied in Supporting Information.

> *Yes, I did find it helpful. It is often hard to comprehend things that we cannot see. Therefore, comparing these things to concepts that we are already familiar with is very beneficial in understanding concepts in chemistry.*

(Student 12919, **AR-1**, **UL-1**)

> *I found the analogy beneficial in understanding the concepts being learned in this lab. The analogy helped me understand that one substance can have a large affect when combined with a specific substance. Separately, two chemicals may not seem that interesting but combined they could have very strange properties that are unexpected. It also matters what ratio these amounts to give them their properties. For example, water (H2O) has three atoms together that has properties very different than oxygen and hydrogen on their own. However, if we added another oxygen molecule creating hydrogen peroxide (H2O2) which is used as bleach the property of the compound changes. The properties of these substances change drastically when changing the composition of the atoms. Using examples that we all understand (analogies) allow me to better visualize what is happening in the example and why they are happening.*

(Student 12856, **AR-5**, **UL-3**)

We note that in the examples above, the students who scored higher wrote longer responses. This observation was frequently made. We discuss this effect further in the Discussion section when various correlations are examined.

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We also categorized 77 students (15% of 501 students) as expressing some type of reservation. Student reservations of analogy have been noted in the literature.[26] Eight students expressed reservation that a different approach would be more useful for them (8 out of 77; representing 2% of the 501 students), with an example shown here:

> *not really due to the fact that I felt I could understand the lab without the use of an analogy, I felt it was easier to understand using my own words and terms, and my own thoughts on the matter.*

(Student 12461, **AR-2**, **UL-2**)

We found that the largest category of reservations (54 out of 77 students; representing 11% of the 501 students), were because students thought themselves familiar with the concept or thought the concept was easy enough to understand so they did not need the analogy. An example of a student reservation in response to **Q4** is shown here:

> *I think that if I didn't already know about chemical reactions it would have helped but since I already knew it didn't really help.*

(Student 12288, **AR-2**, **UL-2**)

From the 54 students in this category, 24 students were scored **AR-1**, 11 students were scored **AR-2**, 14 students were scored **AR-3**, and 5 students were scored AR-4. Students' reservation were characterized independently to their AR level, thus we found a range of these levels. The fact that about 2/3 of students in this category scored low on analogical reasoning indicates that most of the students either did not demonstrate a working knowledge of analogy (**AR-1**) or had only a basic understanding of analogy (**AR-2**). This suggests that reservations coincide with lower levels of analogical reasoning.

The remainder of students expressed reservations (15 out of 77; representing 3% out of the 501 students) that fell into different categories, for example, reservation about the sequence of the lab, expressing that an analogy can be confusing, or did not give a specific reason for their reservations.

■ DISCUSSION

Profiles of AR and UL Levels

Our study was aimed at a point in time, approximately 1 week after a single **CORE** lab was completed by a large laboratory class (n = 501). Profiles of student understanding, appreciation of limitations, and perceived benefits of analogy were created to help organize our thinking about one of the pivotal aspects of the **CORE** approach, i.e., the analogical reasoning activity, and to evaluate the potential for pursuing the **CORE** approach as a strategy toward the laudable goal of raising the level of inquiry *en masse* for large introductory chemistry courses.

Our analysis and assignment to different levels of understanding (**AR-1** to **AR-5**) show that most students have a basic or better level of understanding of analogy (75%) and that a majority of these students (61%) are making connections to chemical observations and/or molecular thinking. Of those making connections, 6 out of 10 of the connections involve the more concrete side of the analogy (macroscopic observations), but with a significant portion (4 out of 10) making connections to the more abstract side of the analogy. Another goal was to determine the overall profile for the appreciation that analogies have limitations. Our results show that a majority of students exhibited a basic (**UL-2**) or better (**UL-3**) appreciation for the limitations of an analogical model. However, a comparison of **UL** and **AR** profiles shows that a higher percentage of students demonstrate an understanding of analogy than demonstrate a basic or better understanding of the limitations (i.e., 75% for **AR-2−5** vs 57% for **UL-2−3**).

Correlation: AR Levels versus Length of Student Responses

As we were analyzing the manifold of student answers to **Q1**-**Q4**, we were struck by the observation that students who wrote longer responses tended to be scored at a higher **AR** level. An example of this effect is illustrated by the two pairs of student responses (**AR-1**, **UL-1** vs **AR-5**, **UL-3**) shown above in the Results section where students described the benefits of using analogy. Table 6 shows the average number of words written in response to **Q1−Q4** as a function of **AR** level. The average number of words written by students who demonstrate a basic or better understanding of analogy (**AR-2** to **AR-5**) is double that of students at the **AR-1** level (140 vs 73 words). We performed a Spearman's Rank Order correlation[59] on **AR** levels vs length of response (n = 501) and there appears to be a positive and statistically significant correlation ($r_s(499) = 0.466$, $p = 0.01$).

Table 6. Average Length of Student Responses at Different AR Levels

AR-level	Average Total Words in Response to Q1−Q4	n
AR-5	191	41
AR-4	144	85
AR-3	136	179
AR-2	118	72
AR-1	73	125

Although longer responses usually contained additional details about the analogy that earned the responses higher scores, it was not just about the length, but the depth of understanding that students conveyed in particular responses that earned the higher scores. A reasonable explanation of this effect is that those students who had a better understanding of analogy had better recall, and were able to provide more elaborate explanations 1 week after completion of the lab. There is some support for this view in the literature. Glynn and Takahashi,[29] have used the teaching with analogy model to develop elaborate science textbook passages for eighth grade students that integrate graphic and text components of an analogy to map the analog to target. They found that students who used these textbook analogies had better 2-week recall and retention compared to the control group. Orgill and Bodner,[26] interviewed biochemistry students who thought that analogies were useful to understand, visualize, and recall information from class. In a recent study, Gentner et al.[62] discussed the curricular implications of using analogies that build upon prior knowledge by

> *...encouraging analogical comparisons that will lead students to form appropriate relational schemas. Students may then be able to retrieve their own examples of key phenomena, thus permitting the prior examples to be reinterpreted in light of current knowledge.*

This result also has implications for more in-depth research on student learning with analogy. That is, the data suggest that more extensive explanations may also be observed in other student work products, such as the construction of the analogy (e.g., Analog to Target Worksheet; see Supporting Information), and the level of details provided in the experimental design used in phase 3, in lab discussions, or lab reports. A benefit of broadening the types of work related to student learning that are examined is

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that it may provide a richer data set to study how students' construction of analogy and use of analogical reasoning are incorporated into laboratory work. From a curricular research point of view, it would be quite important to understand what types of student work correlate with **AR** levels. This may, in turn, provide clues as to the support students need in order to move toward higher levels of inquiry.

A possible alternative explanation is that many students understood the analogy and made connections to laboratory observation and molecular thinking, but did not respond when asked for this information. This would tend to bias the results to be more conservative, i.e., indicating that we underestimate the number of students performing at the higher **AR** levels. While we think this is the less reasonable interpretation, we suggest that interviewing students from various **AR** levels may provide insight into this effect.

Correlation: AR Levels versus UL Levels

In the Teaching with Analogies Model, students identify relevant features of the target and analog, map the similarities, and consider the limitations of the analogy. These aspects are embodied in understanding the analogy (**AR**) and the appreciations for its limitations (**UL**), and so it is of some interest to see if these aspects show correlation. Table 7 shows

Table 7. Percentage of Understanding of Analogy (AL) versus Appreciation of the Limitations of Analogy (UL)[a]

Levels	UL-1 (%)	UL-2 (%)	UL-3 (%)
AR-5	2.2	4.0	2.0
AR-4	5.6	7.2	4.2
AR-3	13.6	15.0	7.2
AR-2	6.2	7.0	1.0
AR-1	15.0	9.4	0.6

[a] $n = 501$.

the profile that includes all five levels of **AR** and three levels of **UL**. Performing a Spearman's Rank Order correlation[59] indicates a weak, positive, but statistically significant correlation between **AR** and **UL** values ($r_s(499) = 0.262$, $p = 0.01$). It is also informative to group students by whether they have "little or no" vs "basic or better" understanding of **AR** and **UL**, and this is illustrated in Table 8. These groups also show a similar weak, positive, but statistically significant correlation between **AR** and **UL**. The correlation originates from the 63% of student responses, which have either low (**AR-1** and **UL-1**, **15.0%**) or high (**AR-2−5** and **UL-2−3**, **47.5%**) **AR** and **UL** values. The other two groups each have one low and one high **AR** or **UL** value and undoubtedly contribute to the weak overall correlation. However, these two groups do not occur equally. Indeed, the group with high **AR** but low **UL** (i.e., 27.5% at **AR-2−5** and **UL-1**) is three times larger than the group with low **AR** but high **UL** values (i.e., 10% at **AR-1** and **UL-2−3**). This result may be important when developing curricula to help students understand analogical reasoning in laboratory settings. For example, it suggests that curricular activities that help students firmly understand analogical reasoning (**AR**) may be effective prior to activities that are designed to develop a depth of understanding about the limitations of analogy (**UL**). Table 9 includes examples of verbatim student responses to explore the comparison between these two groups. The four student responses in Table 9 are from students without appreciation of the limitations of analogy (i.e., **UL-1**) but with different levels of

Table 8. Percentage of Students Grouped by Whether They Have Little or No versus Basic or Better Understanding of AR and UL[a]

Levels	UL-1 (%)	UL-2−3 (%)
AR-2−5	28	48
AR-1	15	10

[a] $n = 501$.

understanding analogy (**AR-2−5**). For this group, all show a basic or better understanding of analogy. Yet in all cases, the written responses are vague regarding appreciation of the limitations. For example, at the **AR-4**, **UL-1** level, a student responds about the importance of appreciating the limitations of an analogy:

> *Yes. If proper understanding of an analogy is not established, the students' ability to better understand the experiment cannot take place.*

(Student 12770, **AR-4**, **UL-1**)

This response suggests it is important to have a "proper" understanding of analogy, but there are no details about what this means or the consequence of not having it. In contrast, the student with **AR-1** and **UL-2**, recognizes that the:

> *analogy is not ever going to be exactly like the original concept. It is just a broader relation that won't have all of the same similarities.*

(Student 12658, **AR-1**, **UL-2**)

While the student has captured an important aspect of the limitation of analogy, his/her understanding about analogy is vague, i.e.,

> *When people relate unfamiliar concepts to their everyday lives it creates a connection between the two and makes the concept much easier to understand.*

(Student 12658, **AR-1**, **UL-2**)

In both groups, students struggle in the dimension that is deficient (i.e., **AR** or **UL**) providing responses that lack specificity and do not make any connections to chemical observations from lab or molecular phenomena in the dimension that is deficient. This is in spite of the fact that some of these students are making connections when describing their stronger dimension. Given the three times higher incidence of **AR-2−5/UL-1** vs **AR-1/UL-2−3**, this evidence suggests that it is more common for students to develop a basic understanding about analogy first. It would be interesting to know if this is then *followed* by the development of how limitations influence understanding. This may have significant curricular implications. For example, could **AR** be developed independent of **UL**? Does **UL** develop only after repeated exposure to analogy and when higher understandings of **AR** have been developed? And would one of these pathways lead to higher incidences of misunderstanding or alternative conceptions?

Other Curricular Considerations

The data show that most students had a basic or better understanding and appreciation of the limitations of analogy. Yet the flip side of this is that 1 in 4 (25%) students did not show much understanding (i.e., **AR-1**) and nearly half (43%) did not appreciate the limitations (i.e., **UL-1**) of an analogy. Given that analogical reasoning is critical for thinking about and understanding science,[2] it would be extremely important to address these students' needs. Several possible strategies are worth mentioning. The first would be to follow these students through

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Table 9. Examples of Verbatim Student Responses Having Basic or Better Understanding of Analogy (AR-2−5) but No Appreciation of the Limitation (UL-1) and Students Not Having a Basic Understanding of Analogy (AR-1) but Having an Appreciation for the Limitation of Analogy (UL-2−3)

Level **AR-2**, **UL-1**	**Q1**: I agree that an analogy can help in describing the invisible chemistry and concepts one can't see. Analyzing and holding something tangible that represents an invisible concept helps to understand something that are not visible. **Q2**: Another analogy that would be help to gain insight as to how polymers work would be elastic bands and another small solid material such as pipe cleaners. This would represent the polymer concept just as the paper clip analogy represented. **Q3**: It is important to think carefully about where an analogy breaks down when using analogies because it helps to understand the invisible concepts. **Q4**: The analogy was very beneficial to my understanding of polymers. By looking at the paper clips and noticing their bonds as they were chains, and then polymers, it was a lot easier to understand. (Student 12675)
Level **AR-3**, **UL-1**	**Q1**: I agree that an analogy can help describe the invisible chemistry and concepts one can't see. For instance in the last lab we did, we compared the polyvinyl alcohol, sodium borate, and the "slime" with paper clips and a paper clip chain. The analogy helped us understand the properties of a polymer, which are invisible. **Q2**: Another analogy that we can compare to the experiment in the lab is mixing water and flour together. Even though flour isn't in liquid form, when the two are combined it forms a new substance that is similar to the "slime" that is formed when you combine polyvinyl alcohol and sodium borate together. The new substance made of water and flour, is very sticky in order to make it perfect it must be a certain ratio of the two substances. Too much of water would make the new substance a watery. **Q3**: It is important to think about the break downs of an analogy because if you don't you won't understand the background of why the two concepts are being compared to one another. **Q4**: The analogy was very beneficial to my understanding of the concepts being learned in this lab. The concepts were compared to each other very well. When we combined the 2 types of paperclips together it was stiffer to move the paperclips around and it would not fall through the funnel; which is similar to adding the polyvinyl alcohol to the sodium borate. Adding the polyvinyl alcohol and sodium borate together also formed a stiffer product, making it difficult to go through the funnel. (Student 12790)
Level **AR-4**, **UL-1**	**Q1**: In order to better understand what is happening chemically within the experiment, representing the chemical bonds with paper clips helps. This way you can fully explain the two chemical chains individually and how when combined a chemical reaction occurs and a bond is created. **Q2**: Paper clips work wonderfully because you can actually connect different clips to represent different molecules or different reactions. However, if a different material would happen to be used climbing chains would work wonderfully and would be more stable than paper clips. However, they may be too large to represent when the slime needs to be placed through the funnel. **Q3**: Yes. If proper understanding of an analogy is not established, the students' ability to better understand the experiment cannot take place. **Q4**: When created the slime it was easy to see that when combining two materials you get one different result. However, chemically not many people had a good understanding of what was going on microscopically. This helped bring that reaction to the macro scale and visually see what reaction was going on, even if it was with paperclips. (Student 12770)
Level **AR-5**, **UL-1**	**Q1**: I agree with the following statement. Especially with chemistry, analogies are a good way to show the basic concepts using examples that we see each and every day. One would be, in the lab we did with the slime. The analogy of using the papers was a good one to show how the different molecules linked together and make the components more sturdy and less easy to pass through a small hole. **Q2**: There is no other analogy that I can think of that would help gain insight in this lab. **Q3**: It depends on how far the analogy goes and how descriptive of an analogy the chemistry concepts need. **Q4**: I did find the chemistry analogy beneficial for my understanding. Using the paperclips helped me understand how the molecules within a polymer link together to form a much sturdier bond making it denser and harder to pass through small spaces. (Student 12294)
Level **AR-1**, **UL-2**	**Q1**: Yes I agree. When people relate unfamiliar concepts to their everyday lives it creates a connection between the two and makes the concept much easier to understand. **Q2**: I couldn't think of another analogy. I think the one we used in the lab worked fine. **Q3**: Yes because an analogy is not ever going to be exactly like the original concept. It is just a broader relation that won't have all of the same similarities. **Q4**: Yes I did. I wasn't entirely comfortable with the concept before doing the lab but now I feel confident in what we learned. (Student 12658)

additional **CORE** experiments. The idea would be to see if repeated exposure is beneficial and would result in a portion of these students obtaining a higher level of **AR** and **UL** understanding. The second would be to focus on exercises before the lab experiment, such as having students consider multiple "concrete" analogies.[29] Another strategy would be to alter the lab procedures to have students present the results of their analogy to each other in more elaborate ways, such as producing posters and making presentations, which would create additional student-to-student interactions, discussions, and questioning.

It is also worth mentioning that 11% of students had reservations about analogy because they were familiar with the analogy and thus not challenged. These students may be considered the other end of the spectrum from those students having difficulty with the analogy. Data from studies by Spier-Dance et al.[60] have suggested that student-generated analogies promote conceptual understanding, while Harrison has stressed the importance of the affect dimension on student engagement of analogy.[61] With these results in mind, we have now created a new callout box in the lab procedure (not available to the students who did the lab in our study) that is called Extra Challenge - Extra Credit. The purpose is to challenge those students who find the analogy to be "too simple". For the Polymers and Cross Linking lab, the Extra Challenge - Extra Credit section asks students to extend the analogy, and several examples are provided of ways they could do this. For example, students could consider the effects of properties such as hydrogen bonding, solvent viscosity, the relative size of objects, three-dimensional steric effects, electronic effects, or the relative ease by which links are made or broken. To obtain extra credit, students need to identify in their lab reports how the modified analogy strengthens their understanding or insight of the chemical phenomena under examination. Anecdotally, many students choose to try for these extra points, though the effectiveness of such an approach has yet to be fully evaluated.

■ CONCLUSIONS AND IMPLICATIONS OF RESULTS

Data from this study were collected at a single point in time at the very beginning of a lab course. An important aspect of the methodology was sampling a large number of students ($n = 501$). Analysis of the data set gave rich details about student thinking and allowed an estimation of the relative levels of understanding of **AR** and **UL** dimensions, using a framework developed from structure-mapping theory.

The data indicate that a majority of students have a basic or better understanding of analogy (**AR**), appreciate the limitations of analogy (**UL**), and make some connections to chemical observations and/or molecular thinking. Many students described details about how analogy benefited them and the usefulness of having tangible representations to help them think about the submicroscopic level. On the **AR-1−5** scale, the weighted average for the class is 2.7, while for the **UL-1−3** scale, the average is 1.7. While this data suggests the average student has the capacity to understand and engage in analogy connected through lab activities, it also reveals significant room for improvement.

The correlations between **AR** and **UL** dimensions and the length of student responses and understanding analogy requires further investigation. The observation that students develop a higher level of understanding of analogy before they can appreciate its limitation suggests areas of curriculum development. The data suggest that additional support is needed for some students.

Our study has shed light on students' understanding of analogies and their use in the laboratory environment. Data from

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this study can inform follow-up studies as well as studies in other domains that utilize analogies for science learning and understanding. A natural follow-up study is to measure student understanding of analogy over time, with repeated treatments of different **CORE** experiments and the use of multiple data streams associated with each specific experiment. Thus, analysis could utilize the Analog to Target Worksheet, the experimental design used by students in phase 3, and lab reports. Additional sources of data could be acquired by sampling student discussions in the lab, videotaping in-lab experimentation, and conducting interviews.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00230.

Other examples of student work and a summary of the Polymers and Cross Linking experiment, including the Analog to Target Worksheet (PDF, DOCX)

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Notes

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